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Groundwater Quality Monitoring Recommendations for In situ Oil Shale Development

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16. ABSTRACT

This study addresses the two primary groups of uncertainties regarding the implementation of a groundwater quality monitoring program for MIS oil shale development such as proposed for Federal Prototype Lease Tracts C-a and C-b (see Figure 1). Hydrogeologic characterization, an essential element in siting monitor wells and for the design of the wells to obtain consistent and representative samples, is discussed in terms of geophysical and hydraulic methods that are employed on the Federal Tracts. These methods are also appropriate for other areas with oil shale stratigraphy. Geophysical and hydraulic methods are evaluated and ranked relative to cost, potential effectiveness, and availability of testing equipment in the oil shale region. Sampling methods are discussed, covering a wide variety of monitoring elements including: (1) well design, (2) monitor well placement, (3) sample collection methods, (4) sampling frequency, (5) sample preservation and handling, (6) selection and preservation of constituents for monitoring, (7) sample analysis, and (8) interpretation of water quality data. A discussion of these monitoring elements is presented in the following paragraphs with detailed information provided throughout the text.

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GROUNDWATER QUALITY MONITORING RECOMMENDATIONS FOR IN SITU OIL SHALE DEVELOPMENT

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PREFACE

On behalf of the Environmental Protection Agency (EPA), Kaman Tempo is conducting a three-year program dealing with the design of groundwater quality monitoring programs for western oil shale. The type of oil shale development being evaluated in this study is modified in situ (MIS) retorting as presently proposed for Federal Prototype Lease Tracts C-a and C-b in western Colorado. This study focuses specifically on the monitoring for in situ retorting on the Federal Lease Tracts and has followed a stepwise monitoring methodology.

This report represents the final phase of this research program. The goals of the first phase were to:

- Review MIS monitoring programs and development with regard to potential impacts on groundwater quality
- Use this review to identify the key issues, uncertainties, and unknowns with regard to design and implementation of groundwater quality monitoring programs for MIS retorts.

The goal of this phase was to:

- Protect groundwater quality by developing specific monitoring recommendations for the use of geophysical logs and aquifer testing methods for MIS oil shale development.

Monitoring recommendations are provided for the use of the following logs: temperature, caliper, gamma, spinner, radioactive tracer, velocity, sonic, density, electric, and seisviewer. In addition, monitoring recommendations are presented on four hydraulic testing methods and a complete program for sample collection, preservation, and handling at MIS operations.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS AND SYMBOLS

bpd	barrels per day
°C	degrees Centigrade
cfs	cubic feet per second
EPA	U.S. Environmental Protection Agency
EMF	electromotive force
°F	degrees F
ft/min	feet per minute
ft	foot, feet
ft^2	square foot, square feet
g	gram(s)
gm/cc	grams per cubic centimeter
gpm	gallons per minute
gal/ton	gallons per ton
MDP	mine development phase
meq	milliequivalent
mg/l	milligrams per liter
MIS	modified in situ
ml	milliliter(s)
PVC	polyvinyl chloride
RBOSC	Rio Blanco Oil Shale Company
SP	spontaneous potential, self-potential
SPI	secondary porosity index
USGS	U.S. Geological Survey
µmho/cm	micromhos per centimeter
µsec	microsecond(s)
3-D	three dimensional

CHEMICALS, IONS, CONSTITUENTS

CO_2	carbon dioxide
$CuSO_4$	copper sulfate
DOC	dissolved organic carbon
H_2SO_4	sulfuric acid
H_3PO_4	phosphoric acid
HNO_3	nitric acid
I	iodine
MBAS	methylene blue active substances
$NaHCO_3$	nahcolite
NaOH	sodium hydroxide
NTA	nitrilotriacetic acid
TDS	total dissolved solids

FORMULAE ABBREVIATIONS

A	length of test section
c	hydraulic resistance
Cu	conductivity coefficient, unsaturated
Cs	conductivity coefficient, saturated
h1	static water column head
h2	applied pressure
H	effective head
k	hydraulic conductivity
K	permeability coefficient
kD	aquifer transmissivity
Ko	Bessel function
L	leakage factor
m	slope
Q	constant recovery (drawdown) discharge
q_i	ith flow interval
q_n	last flow interval
r	distance from pumping well
s	drawdown
S	storage coefficient
Sp	inflection point
T	transmissivity
T_e	effective transmissivity
t_i	flow time for each change in rate
t_n	total flow time
T_n	transmissivity in the direction $(\theta+\alpha)$ with the x-axis
tp	time corresponding to Sp
T_x	transmissivity on major flow axis
T_y	transmissivity on minor flow axis
Δ_s	change in slope
Δt	interval transit time
Δt_f	fluid interval transit time
Δt_{ma}	matrix interval transit time
Δp	change in pressure
u	porosity
x	percentage of unsaturated strata
ϕ	porosity

ENGLISH/METRIC CONVERSIONS

°Fahrenheit	(°Centigrade x 9/5) - 32
1 gallon	3,846.2 cubic centimeters; 3.86 liters
1 barrel	0.16 cubic meter
1 cubic yard	0.77 cubic meter
1 cubic foot	0.028 cubic meter
1 acre-foot	1,250 cubic meters
1 pound	0.0005 tonne (metric ton); 487.8 grams
1 acre	0.0004 hectare
1 quart	0.9463 liter
1 foot	0.305 meter
1 square mile	2.49 square kilometers
1 ton (short)	0.909 tonne (metric ton)

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-- Ms. Marla Moody

C-b Oil Shale Venture

-- Mr. R.E. Thomason

-- Mr. C.B. Bray

SECTION 1

INTRODUCTION

BACKGROUND

Synthetic petroleum products recovered from western oil shales are expected to play an important part in supplying energy needs of the United States during the later part of the 1900's. Various estimates of the magnitude of western oil shale reserves have been made. The U.S. Geological Survey estimates that an equivalent of about 4,000 billion barrels* of oil are contained in the oil shales of the Green River Formation of Utah, Colorado, and Wyoming. These oil shale resources account for 80 percent of the known world resources but, of course, are not completely recoverable. Recoverable resources are a function of mining and retorting technology and economics, but may amount to about 1,800 billion barrels of oil (Hendricks and Ward, 1976). As the estimated remaining world ultimate oil resources are about 2,000 billion barrels (Tiratsou, 1976), of which less than 150 billion barrels are in the United States, western oil shale is clearly a significant energy resource.

Federal Prototype Lease Development

The current Federal Prototype Oil Shale Leasing Program, administered by the U.S. Department of Interior, was initiated in 1969. Program planning and environmental evaluation efforts by various government interagency and industry groups culminated in preparation of a draft environmental impact statement in 1971. Informational core hole drilling by firms interested in obtaining oil shale leases was conducted in the 1971 through 1973 period. This led to nomination of 20 potential lease tracts in Colorado, Utah, and Wyoming. The Department of Interior selected six tracts for the prototype leasing program. The environmental impact statement was finalized in 1973. Later in 1973, the first lease sale was initiated. In January 1974, successful bidders for the two Colorado lease tracts (C-a and C-b) and for two Utah tracts (U-a and U-b) were announced. No bids were received on the proposed Wyoming lease tracts.

Environmental baseline and operation design studies were conducted over the two years following the lease initiation. In 1976, Detailed Development

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* See p. xiii for conversion to metric units. English units are used in this report because of their current usage and familiarity in industry and the hydrology-related sciences.

Plans (DDP) were submitted for both Tracts C-a and C-b. The initial DDP for Tract C-a called for open pit mining, surface retorting, and off-tract locations for processing facilities, overburden, and processed shale disposal. A number of serious problems, in particular approval for off-tract disposal of wastes, could not be resolved and a lease suspension was requested. This suspension was granted in September 1976. During this suspension, a revised DDP for Tract C-a was prepared calling for modified in situ (MIS) development plus surface retorting of the oil shale mined from development of the MIS retorts. This revised DDP was submitted in May 1977 and was subsequently approved by the Area Oil Shale Supervisor (AOSS).

Initial development plans on Tract C-b (by Ashland Oil, Inc. and Shell Oil Company) were submitted in February 1976. This plan called for a deep mining and surface retorting (and disposal) operation. Development was suspended later in 1976. In November of that year, Shell withdrew from the C-b Oil Shale Project and Ashland formed a new venture with Occidental Oil Shale, Inc. A revised DDP proposing MIS operations was submitted in February 1977. Site development was initiated in the fall of 1977.

Shale deposits in the Piceance Basin that can potentially be exploited by in situ technologies underlie an area of considerable topographic variation that is largely undeveloped. A wide range in both hydrologic and geologic conditions occurs throughout the area containing the deposits. Several in situ technologies are available, each of which could have characteristic impacts. There has not been sufficient experience with the various retorting methods to determine which is the most suitable in terms of minimizing environmental harm in the Piceance Basin. It may appear at first glance that in situ retorting has less potential for impact to the environment than surface retorting; however, the long-term impact to the subsurface environment may prove this assumption to be wrong.

Monitoring of groundwater quality impacts associated with in situ oil shale development will be difficult. Retort waters produced by small-scale in situ operations have resulted in the identification of a wide spectrum of potential pollutants. Research to date indicates that many of these pollutants have only recently been classified, while others are still under investigation. It is not clear if the quality of the retort waters from small-scale in situ retorting will be similar to those waters produced by large-scale commercial in situ retorts.

The Federal Water Pollution Control Act Ammendments of 1972 (P.L. 92-500) and the Safe Drinking Water Act of 1974 (P.L. 92-523) provide for protection of groundwater quality. These mandates call for programs to prevent, reduce, and eliminate pollution of both navigable waters and groundwater and for particular protection of drinking water resources. Similar goals are embodied in the Toxic Substances Control Act of 1976 and the Resource Conservation and Recovery Act of 1976. The national responsibility for these various activities is given to the U.S. Environmental Protection Agency (EPA). Various State agencies also have similar responsibilities via State enabling legislation.

PREVIOUS WORK

A companion report to this study, developed at Tempo and prepared by Slawson (1980b), presents the results of a groundwater monitoring design study of in situ oil shale development. The approach used in that study is the general monitoring methodology developed by Tempo as follows:

Monitoring Step	Description
1	Select Area for Monitoring
2	Identify Pollution Sources, Causes, and Methods of Disposal
3	Identify Potential Pollutants
4	Define Groundwater Usage
5	Define Hydrogeologic Situation
6	Describe Existing Groundwater Quality
7	Evaluate Infiltration Potential of Wastes at the Land Surface
8	Evaluate Mobility of Pollutants from the Land Surface
9	Evaluate Attenuation of Pollutants in the Saturated Zone
10	Prioritize Sources and Causes
11	Evaluate Existing Monitoring Programs
12	Identify Alternative Monitoring Approaches
13	Select and Implement the Monitoring Program
14	Review and Interpret Monitoring Results
15	Summarize and Transmit Monitoring Information

In particular, the companion report focused on modified in situ development as proposed for Federal Prototype Lease Tracts C-a and C-b in Colorado by developing data required for an initial pass through methodology steps 1 through 13, although step 13 is not fully implemented. The methodology, in general, and its application to monitoring design problems are described in several other reports (Everett, 1979, 1980; Todd et al., 1976; Slawson, 1979) and will not be presented here in detail.

A preliminary monitoring design/implementation framework has been developed for MIS retorts in the companion report. This work lead to the identification of areas of uncertainty with regard to implementation of groundwater quality monitoring programs for in situ facilities. These uncertainties were found to be primarily within (1) hydrogeologic characterization and (2) sampling methods utilized at the MIS retorts.

PRESENT STUDY

This study addresses the two primary groups of uncertainties regarding the implementation of a groundwater quality monitoring program for MIS oil shale development such as proposed for Federal Prototype Lease Tracts C-a and C-b (see Figure 1). Hydrogeologic characterization, an essential element in

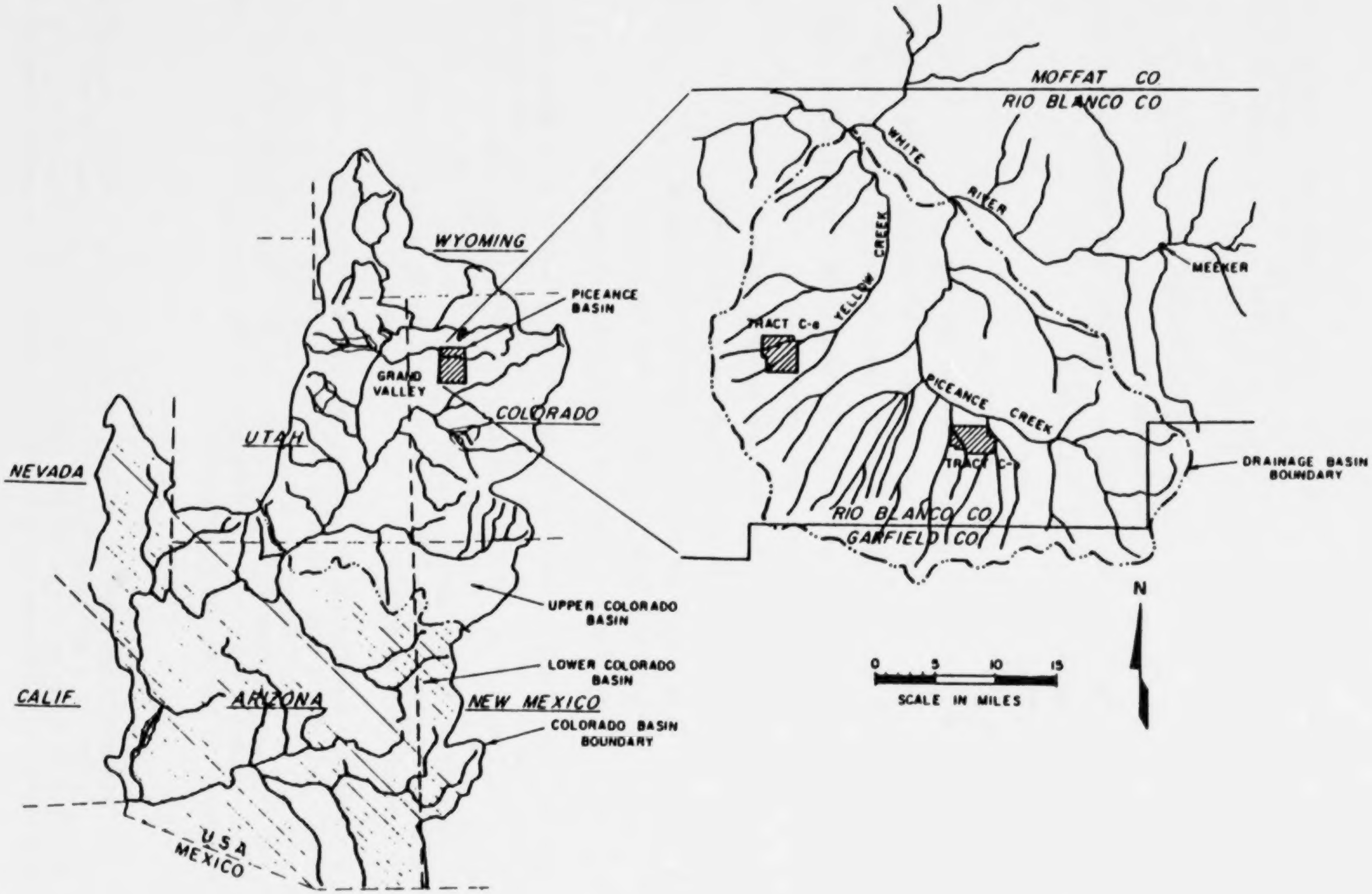
WYOMING
PICEANCE BASIN
GRAND VALLEY
COLORADO
UTAH
NEVADA
CALIF.
ARIZONA
NEW MEXICO
USA
MEXICO
UPPER COLORADO BASIN
LOWER COLORADO BASIN
COLORADO BASIN BOUNDARY
MOFFAT CO
RIO BLANCO CO
WHITE RIVER
MEEKER
YELLOW CREEK
TRACT C-a
PICEANCE CREEK
TRACT C-
RIO BLANCO CO
GARFIELD CO
DRAINAGE BASIN BOUNDARY
N
0 5 10 15
SCALE IN MILES

Figure 1. Location of Tracts C-a and C-b study area in Piceance Creek Basin.

siting monitor wells and for the design of the wells to obtain consistent and representative samples, is discussed in terms of geophysical and hydraulic methods that are employed on the Federal Tracts. These methods are also appropriate for other areas with oil shale stratigraphy. Geophysical and hydraulic methods are evaluated and ranked relative to cost, potential effectiveness, and availability of testing equipment in the oil shale region. Sampling methods are discussed, covering a wide variety of monitoring elements including: (1) well design, (2) monitor well placement, (3) sample collection methods, (4) sampling frequency, (5) sample preservation and handling, (6) selection and preservation of constituents for monitoring, (7) sample analysis, and (8) interpretation of water quality data. A discussion of these monitoring elements is presented in the following paragraphs with detailed information provided throughout the text.

SECTION 2

SUMMARY

HYDROGEOLOGIC CHARACTERIZATION

A program designed to characterize the hydrogeology of an oil shale tract prior to designing a groundwater quality monitoring program should include a proper suite of geophysical logs and appropriate aquifer testing methods. This report discusses these subjects and presents recommendations for their use in the design and implementation of groundwater quality monitoring programs for MIS retorting areas.

Geophysical Methods

Several logs were evaluated in this study to determine their overall effectiveness in providing environmentally pertinent and reliable hydraulic data. Those logs evaluated include:

Temperature

Caliper

Gamma-ray

Spinner

Radioactive tracer

Velocity

Sonic (acoustic)

Density

Electric

Seisviewer.

With the exception of the seisviewer log, all the logs listed above were found to be comparable to each other in cost. Accordingly, recommendation of geophysical logs is based on effectiveness in obtaining reliable hydraulic data.

The following log suite is recommended for its utility for hydrogeologic characterization: temperature, caliper, sonic, and electric logs. Of more limited value and receiving secondary, or lower, priority ranking are gamma-ray, velocity, density, and spinner logs. The radioactive tracer and seisviewer logs are not recommended for obtaining hydraulic data for the design of groundwater monitoring strategies at oil shale development sites.

Hydraulic Methods

Tempo's previous study (Slawson, 1980a) indicated a need for aquifer testing and recommended that selected exploration and core holes be converted to serve as testing wells. Existing wells can be conditioned or new wells constructed to be of sufficient size to accommodate pumps for aquifer testing.

Four general methods of hydraulic testing procedures have been evaluated and are classed as follows:

Drill stem tests

Dual packer tests

Long-term pump tests

Single packer tests.

Review of the testing procedures, equipment costs, and utility of the resulting data has produced the following priority ranking:

1. Dual Packer Tests provide specific hydrologic data at a minimal cost when multiple tests are conducted in a single borehole. Down-hole test equipment assembly allows for pumping, injection tests, and discrete water quality sampling.
2. Long-Term Pump Tests produce the most representative data on boundary conditions and flow patterns and are especially effective for determining regional groundwater conditions. Long-term pump tests should be carefully planned and positioned to provide maximum data per test because their use is limited by the rather large expense of implementation.
3. Single Packer Tests provide horizon specific data similar to the dual packer method. However, for each test, the packer must be inserted and removed from the borehole. This labor intensive activity can significantly increase the cost of data acquisition.
4. Drill Stem Tests are commonly run during drilling operations. They are of value when single, well-defined aquifer systems are penetrated. However, when multiple aquifers are encountered during drilling, interpretation of data resulting from drill stem tests becomes extremely difficult. Drill stem tests are therefore not recommended for determining hydraulic parameters in complex hydrologic environments.

SAMPLING METHODS

The objective of a groundwater monitoring strategy in the oil shale region where MIS retort development could be selected as the mining methodology is to (1) provide baseline groundwater quality data, (2) detect and measure groundwater flow within the abandoned retort interval, and (3) detect changes induced by waste residuals (e.g., spent shale, retort water) within the abandoned retort zone. Compilation of baseline data and accurate evaluation of the latter two aspects require collection of representative groundwater quality samples. However, a number of factors can influence the representative nature of the groundwater samples collected. These factors include well design, sample collection methods, and sample handling procedures.

Well Design

The Upper and Lower Aquifer zones present in the Piceance Basin, Colorado, are composed of numerous layers, each of which can possess variable water quality and quantity characteristics. Since numerous wells are open or perforated over the entire Upper or Lower Aquifer interval, the water quality data collected from these wells represent a composite of all penetrated layers. On the other hand, a layer exhibiting greater hydrostatic head than adjacent layers can influence portions of the well bore, resulting in collection of a water quality sample that represents the high head layer and not a composite of the entire open interval. Under both of these conditions, baseline water quality data collected may not be adequately measured in detail, and for operation/abandonment phase monitoring, groundwater flow through abandoned retorts may not be adequately represented. Furthermore, any trace constituents or potential contaminant present may be sufficiently reduced below detection limits due to the composite nature of the well design if mixing does occur.

A network of multiple completion wells is the recommended approach for a groundwater monitoring program near the retort fields. Multiple completion well design will enable the collection of representative data from each of the intervals potentially affected by the oil shale retorting operation. The suggested specifications for this type of well are:

- Steel casing and polyvinyl chloride (PVC) well construction material. Although the structural properties of PVC may preclude its use as a casing material, the inert characteristics of PVC make it ideal as a well construction material. PVC is also inexpensive when compared with other materials.
- The diameter of the PVC should be large enough to accommodate a submersible pump. The recommended diameter and wall thickness of the PVC is 6 inches OD and schedule 40 (19/64 inch), respectively.
- Each well of the multiple completion should be completed in a different interval using cement grout to prevent the interconnection of different intervals.
- Wells should be developed thoroughly, i.e., fresh water circulated in the well bore, to remove any traces of drilling fluid or other materials that may affect water quality samples.

It appears that wells completed over the entire Upper or Lower Aquifer are suitable for groundwater monitoring in areas removed from the retort field(s). This open type of well design will provide general information on the regional water quality and does not require the finer levels of completion necessary for wells close to the retort field(s). It is recommended that the same specifications suggested for the multiple completion wells be utilized for the more regional wells if samples are to be collected via a submersible pump.

The recommended specifications presented above are designed to allow for sampling with a submersible pump. Although pumping samples is the best approach from a technical standpoint, there are some distinct trade-offs with respect to the construction costs associated with the larger diameter wells. There are also some significant trade-offs with respect to sampling costs.

The approximate costs for the well development are:

Design	Approximate Cost per Well (dollars)[a]
Large Diameter (6-inch) Well[b]	
Upper Aquifer single completion	18,000 - 20,000
Lower Aquifer single completion	35,000 - 38,000
Multiple completion	53,000 - 58,000
Smaller Diameter (2-5/8-inch tubing strings) Wells[c]	
Dual completion (i.e., two completion strings with one open over the entire Upper Aquifer and one open over the entire Lower Aquifer	35,500 - 38,000
Multiple completion	39,000 - 44,000

Notes:

[a] These costs include drilling, development, casing material, etc. in 1980 dollars.

[b] Submersible pump can be utilized for sample collection.

[c] Bailer can be utilized for sample collection.

These cost data show that large-diameter single and multiple completion wells are more expensive than smaller diameter dual and multiple completion wells, respectively. In addition, the cost for an entire groundwater monitoring program would be substantially higher and equal to the cumulative cost of all wells in the system. The approximate costs of an entire groundwater monitoring program, including sampling, are presented in Table 1 of this section.

TABLE 1. WELL CONSTRUCTION AND SAMPLING COSTS FOR DEEP AQUIFER WELLS (1980 dollars)

Item	Fixed Submersible Pump	Portable Submersible Pump (USGS)	Bailing (Tract C-a)	Swabbing (Tract C-b)
Well Construction	53,000-58,000[a]	53,000-58,000	35,500-38,000	39,000-44,000
Sampling Costs				
Capital Requirements	61,800-79,800	55,000-60,000	8,000-10,000	N/A[b]
Operational Requirements (Quarterly)	200-400	1,400-1,700	200-400	16,000-18,000
Labor (quarterly)	135-200[c]	11,200-14,000[d]	135-200[c]	3,500-4,300[e]
Five-year Total (including construction of 12 monitoring well sites)	704,500-787,800	943,000-1,072,000	440,700-478,000	858,000-974,000

Notes:

[a] Assumes similar well construction for fixed pump as with portable pump.

[b] Tract C-b contracts swabbing rig, thereby eliminating capital requirements.

[c] Assumes sampling eight wells per day.

[d] Assumes sampling one well per day.

[e] Assumes sampling three wells per day.

Monitor Well Placement

One of the goals of hydrogeologic characterization efforts is to allow description of groundwater flow patterns within and near a retort field. The purpose of this description is to locate monitoring wells so as to sample flow through and from the retort field area. Monitor wells should be located as follows:

1. Near retort field (within a few hundred feet) and within the field
2. Oriented downgradient of the MIS retorts along fracture lines and major axis of anisotropy as defined by geologic testing program
3. Accessible for sampling equipment.

Construction of new wells may be required for operation/abandonment monitoring. Wells constructed for hydrogeologic testing may not be appropriately located for inclusion in the monitoring program.

Sample Collection Methods

Sampling of deep aquifer wells on Federal Lease Tracts C-a and C-b reviewed in this study is accomplished by bailing and swabbing, respectively. Although these techniques obtain the desired results of collecting a sample, there is some question as to the representative nature of the sample collected. Some factors contributing to the problem of collecting a representative sample using these techniques follow.

Problems associated with bailing are:

- The water column chemistry can become stratified due to variations in water quality and hydrostatic head in the different layers penetrated by the well. Although this is a function of well design, nonrepresentative samples will be bailed from this well if the samples are collected inconsistently with respect to depth. Water quality data are more representative if samples are collected consistently adjacent to the water-producing intervals.
- The water present in the well casing above the open, or perforated, section can be isolated from the aquifer water. Samples collected from this portion of the well will be nonrepresentative of the aquifer water chemistry.
- Small deviations in the sample collection depth can significantly affect the data when a bailer is being employed. The potential magnitude of this effect is apparent from the profile sampling data presented in this report.

These potentially negative influences can be alleviated if correct bailing procedures are exercised. The recommended procedure for bailing groundwater samples is as follows:

1. Use a flow-through type bailer (e.g., Kemmerer sampler). Bailers that are open at the top and sealed at the bottom do not have this flow-through characteristic and will generally be filled with the first water encountered in the well (i.e., water near the static water level).
2. Compile well completion data. Of particular importance is the well diameter, depth to aquifer, aquifer thickness, and total depth.
3. For shallow wells with very slow groundwater movement, estimate the well volume from the well completion data and extract at least one well volume previous to sample collection. For both shallow and deep wells with rapid groundwater movement, select a sampling point adjacent to the aquifer.
4. Consistently sample from the same depth and adjacent to the aquifer during every sampling effort.
5. Measure temperature, specific conductance, and pH in the field.

If these guidelines are followed, bailing is a very effective method for collecting groundwater quality samples. In addition, bailing is the most cost-effective approach (see Table 1).

Swabbing a well is a more representative sampling technique than bailing in that a well volume can be removed prior to sample collection. However, this technique is very expensive to employ and presents a potential for contamination.

The following problems are associated with swabbing:

- There is high potential for introducing organics into the sample when oil-field equipment is used. Care must be taken to clean the swabbing equipment thoroughly.
- The amount of water swabbed from a well is difficult to determine, and can result in obtaining inconsistent and nonrepresentative samples. If possible, the discharge should be carefully measured to provide the necessary data for collecting consistent and representative data.
- Swabbing may accelerate plugging of perforations in the well.
- Swabbing is extremely expensive and time-consuming.

Due to these factors, swabbing should not be employed as a sampling method.

For the deep wells to be utilized for monitoring modified in situ retorts, pumping is the recommended sampling approach from a technical standpoint. Pumping allows a greater portion of the aquifer to be sampled, minimizes the effects well casing or water stratification may have on the sample representativeness, and reduces the potential for missing or delaying the observation of mobile pollutant constituents. In addition, a submersible pump can be fixed in the well or be used as a mobile unit, alternatives which can be very beneficial to a sample collection program. However, on a cost-effective basis, the fixed submersible pump is suggested for deep aquifer wells (see Table 1).

The following procedure is recommended for collecting a representative sample from a well when using a submersible pump:

1. Compile well construction data, including well diameter, total depth, and perforated interval, or aquifer interval in an open well.
2. Measure static water level and estimate well volume.
3. The pump intake should be placed approximately 5 feet above the open, perforated, or screened aquifer interval.
4. The discharge rate should be maintained at a moderately low rate to prevent excessive drawdowns in the aquifer and well, as well as minimizing turbulent mixing in the annulus.
5. At least one well volume should be extracted from the well before sampling.
6. The parameters most easily monitored in the field are specific conductance, pH, and temperature. These parameters should be measured continuously throughout the pumping period. Continuously monitoring these parameters is particularly important for infrequently sampled monitor wells.
7. A sample should be collected only after the field parameters have stabilized for a period of time. The data provided in the text indicate that conductivity is the most representative parameter of infusion of aquifer water in the well bore or casing. However, it is suggested that all of the parameters (i.e., pH, temperature, and specific conductance) be utilized to determine representative aquifer water to prevent premature sample collection due to the failure of field apparatus.
8. The sample should be collected as close to the well head as possible to avoid potential contamination, precipitation of solutes, and the loss of dissolved gases.

In addition to providing consistency with respect to pump placement, field measurements, etc. among the different sampling dates, these recommendations also provide a means for establishing the sampling protocols for each well. This is an important aspect in that the data presented in Section 3 indicate the duration of pumping required for an equilibrated discharge may vary substantially from well to well. Therefore, the individual testing of each well is critical to representative sample collection. In addition, these protocols should be updated periodically for each well, particularly for wells with large open intervals.

In addition to the technical aspects, there are some cost considerations that need to be evaluated. Table 1 provides the approximate sampling costs for four different sampling methods and corresponding well design necessary for the sampling tool. The sampling methods evaluated were a fixed submersible pump, portable submersible pump, bailing, and swabbing. For comparison purposes, the costs for each sampling method were developed under a quarterly sampling frequency of 12 Upper and Lower Aquifer wells for a 5-year period.

Based on the data presented in Table 1, it is apparent that the bailing method is the best approach from a cost perspective. The portable submersible pump and swabbing methods are very expensive compared with the bailing method and, therefore, are not recommended. Although the fixed submersible pump clearly has some economic trade-offs when compared with bailing, there are some technical advantages to using this approach and the fixed pump should not be ruled out. The data comparing samples collected by bailing with samples collected by pumping for deep aquifer wells indicate that more representative samples are collected via a pump. Therefore, it is recommended that each method be evaluated according to the type of well design and the overall monitoring strategy. It appears that the bailing method works well for the "near-retort" type of well designs (i.e., wells with fine levels of completion), whereas a fixed submersible pump provides better results in wells that are completed over a large interval.

Sampling Frequency

Proper selection of well sampling frequency is a function of potential pollutant mobility, and when hard data are not available, the selection is often made by trial and error. Shallow groundwater systems commonly display response to seasonal or otherwise cyclic events of recharge and infiltration of dissolved constituents from the surface. Regional pumping patterns can also affect the variability of water quality in both deep and shallow wells. Such variability would necessitate relatively greater sampling frequencies.

The aquifers to be monitored for the impacts of abandoned MIS retorts are relatively deep and not subject to great variability from recharge events. Such influence of cyclic events is usually attenuated during slow passage through the aquifer. Hence, a somewhat low sampling frequency is appropriate.

Another consideration is the sequence of events leading to abandonment, namely, mine-retort operation, termination of retorting, termination of dewatering, and recovery of aquifer water levels in the mine-retort area. During the operational phase, particularly when dewatering is appreciable, no releases would be anticipated from the MIS retorts. Thus, low-frequency sampling (e.g., annual) would be adequate. If dewatering is via wells (rather than strictly from the mine itself), the dewatering wells (sampled individually) may be an acceptable location for sampling. Any groundwater flow within the retort field during this dewatering phase would be dominated by and directed toward the dewatering wells. Thus, any appreciable groundwater movement in the retort interval would be effectively sampled by these wells.

During the time from cessation of dewatering through stabilization of water levels, the groundwater system would be in a state of flux and rapid changes in water quality may occur. During this period, more frequent sampling is recommended. Initially, monthly sampling is appropriate to establish patterns of temporal variability. This frequency can then probably be diminished to semiannual and then perhaps to annual as time trends are established. Several years may pass before these low frequencies are appropriate.

Sample Preservation and Handling

Delayed receipt of samples at the analytical laboratory and incorrect preservation techniques can significantly adversely affect sample chemistry. To prevent any potential sample modification, the following sample preservation and handling procedures are recommended:

- Sample volumes, preservatives, and containers should be selected according to the EPA-recommended procedures presented in Methods for Chemical Analyses of Waters and Wastes (U.S. Environmental Protection Agency, 1979).
- The samples should be filtered in the field through a 0.45-micron filter before preservation.
- Data on past water quality trends should be consulted to detect any anomalous data during the sampling effort.
- Specific conductance, pH, and temperature should be measured in the field at the time of sample withdrawal. This also applies to oxidation-reduction potential and dissolved oxygen determinations, if desired.
- Accurate field notes should be maintained for future data evaluation. These notes should include: specific times and dates the activities were performed, water levels, source of sample, weather conditions, well completion data, sample collection method, field observations, reason for sampling, field measurements, problems encountered, and the sample collector's identity.
- The samples should be shipped each day from the field to the analytical laboratory via commercial plane or bus. Both methods are reliable and inexpensive, and provide reasonable assurance against prolonged sample storage. If the samples cannot be shipped and received at the laboratory within 24 hours, on-site analytical facilities should be provided.

- The chain of custody for the sample should be recorded and be as limited as possible to prevent excessive sample handling, which can result in shipment and analysis delays. Individuals should be designated both in the field and at the laboratory to maintain adequate quality control with respect to sample handling and analysis activities.

If these procedures are followed, sample handling and preservation techniques should not affect the analytical results.

Selection and Preservation of Constituents for Monitoring

Recommended monitoring constituents for general water quality, major inorganics, organics, and trace metals are given below.

Sample preservation and handling requirements for these water quality parameters are dictated by the nature of the constituents to be analyzed. For the recommended constituents, the holding times listed below are recommended by U.S. EPA (1974). Bottle requirements (plastic versus glass) are also provided in this reference. Filtering of samples immediately after collection is recommended with addition of chemical preservatives in the field at the time of collection or addition of preservatives to sample bottles prior to initiation of field activities. Preservation techniques include:

	Preservative	Maximum holding time
General water quality constituents		
Total dissolved solids (filterable residue)	Cool, 4°C	7 days
Conductance	Cool, 4°C	24 hours
pH	Determine on site	6 hours
Alkalinity	Cool, 4°C	24 hours
Major inorganics		
Calcium, magnesium, potassium, and sodium	Nitric acid to pH < 2	6 months
Bicarbonate	Cool, 4°C*	24 hours*
Carbonate	Cool, 4°C*	24 hours*
Chloride	None required	7 days

(continued)

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* Assumed same as alkalinity.

	Preservative	Maximum holding time
Major inorganics (continued)		
Nitrate	Cool, 4°C	24 hours
Sulfate	Cool, 4°C	24 hours
Fluoride	Cool, 4°C	7 days
Ammonia	Cool, 4°C, sulfuric acid to pH < 2	24 hours
Phosphate	Cool, 4°C	24 hours
Organics		
Dissolved organic carbon	Cool, 4°C, sulfuric acid to pH < 2	24 hours
Kjeldahl nitrogen	Cool, 4°C, sulfuric acid to pH < 2	24 hours
Trace metals		
Arsenic	Nitric acid to pH < 2	6 months
Selenium	Nitric acid to pH < 2	6 months
Vanadium	Nitric acid to pH < 2	6 months
Molybdenum	Nitric acid to pH < 2	6 months
Mercury	Nitric acid to pH < 2	38 days (glass container)

The short holding times listed here will be difficult, if not impossible, to accomplish in the remoteness of the oil shale region unless on-site laboratory facilities are developed. Such an approach is recommended for the following:

- Conductance
- pH
- Alkalinity
- Carbonate
- Bicarbonate
- Chloride

- Ammonia (electrode method)
- Fluoride (electrode method).

Since it may not be feasible to meet the listed holding time requirements for many of the constituents listed (e.g., TDS, nitrate, sulfate, phosphate, DOC, and Kjeldahl nitrogen), it is recommended that testing be initiated so that more suitable holding times for the waters in question can be defined and the nature and significance of errors evaluated.

Sample Analysis

Recommendations for sample analysis are as follows:

1. Routine monitoring of recommended constituents listed in the preceding discussion of sample preservation and handling
2. More extensive sample collection and analysis (such as unique indicators discussed in Slawson, 1980a, Section 10) should the routine sampling program indicate an impact of MIS retorts on groundwater quality
3. Use of standard analytical methods.

The constituents listed in the preceding discussion of sample preservation were selected for routine monitoring because high levels are expected should materials leach from MIS retorts. In addition, constituents include those which allow data checks (TDS-conductivity, cation-anion balance, etc.) to be performed as a quality control measure. Should this routine monitoring program indicate an impact of MIS retorts on groundwater quality, more extensive analysis of samples is recommended. This analysis should include the sets of possible unique indicators presented in Slawson, 1980a, Section 10.

This recommended list of constituents includes fewer constituents than the analysis sets of presently implemented monitoring programs, such as outlined in Slawson, 1980a, Section 9. This shortened list should allow detection of groundwater quality impacts due to MIS retorts while economizing on analytical needs.

Other sets of constituents, such as various organic fractionations and stable isotope ratios, need to be evaluated further, particularly the interpretation of such data with regard to indicating the impact of oil shale byproducts. Standard analytical methods, such as presented by U.S. EPA (1974) or in Standard Methods (American Public Health Association, 1976), should be employed.

Interpretation of Water Quality Data

The purpose of interpreting water quality data is to define quality trends, identify new pollution problems or regions of improvement, and assess the effectiveness of pollution control activities. To ensure the utility of the water resource information collected, data analysis procedures include

(1) checks on data validity and (2) methods of presenting the resulting information so it is useful for environmental description or control purposes. Data checking procedures include:

- Cation-anion balance
- TDS-conductivity comparison
- Conductivity-ion comparison (meq/l)
- Diluted-conductance method.

Data presentation and interpretation are key aspects of monitoring for environmental detection and control. Several methods are available for organization and presentation of water quality data. These include tabulation and graphical tabulation of appropriate water quality criteria or standards, providing a format for screening data, and identifying important sites or pollutant constituents. Presentation of ionic concentration as milligrams per liter or milliequivalents per liter and segmentation of contributing components, such as total and noncarbonate hardness or phenolphthalein and methyl orange alkalinity, are useful techniques for data correlation and evaluation. Further discussion of data analysis procedures is provided in Section 3.

SECTION 3

HYDROGEOLOGIC CHARACTERIZATION METHODS

Much descriptive information and data have been published on the geologic and hydrologic characteristics of the oil shale regions of Colorado, Utah, and Wyoming. These studies, however, have been largely regional in scope, leading to a generalized focus on developmental groundwater quality monitoring plans, rather than environmental protection site- and source-specific orientations. The goal of this study has been to develop support information that will provide a procedure for obtaining valid groundwater quality data to provide an evaluation and decision-making framework for design of monitoring programs to protect the environment and water quality at specific development sites. This study is intended to be a planning document that will provide a technical basis and a methodology for the design of groundwater quality monitoring programs for industrial oil shale developers and the several governmental agencies concerned with environmental planning and protection. The Piceance Creek Basin of Colorado, where the richest oil shale deposits lie and where it is expected that most future leasing and industrial development will occur, is discussed in this study. The general procedures and framework for environmentally sound hydrogeologic characterization, however, are valid for other oil shale regions.

Most of the hydrogeologic characterization methods described in this study will be employed during the initial exploration/resource evaluation phase of industrial development. Some methods will be employed during the mine development phase, while others, such as sample collection for ongoing water quality monitoring, will be conducted over the entire life of the project, including the postclosure period.

To plan, design, and conduct a hydrogeologic characterization program as a basis for designing a groundwater monitoring strategy, a general understanding of basin hydrogeology is necessary. The following subsections describe the Piceance Basin hydrogeology.

GENERAL BASIN HYDROGEOLOGY

The area contains three important aquifer systems: the Lower Aquifer, the Upper Aquifer, and the alluvial aquifers. The Lower Aquifer occurs in the Parachute Creek Member below the Mahogany Zone, and the Upper Aquifer is above the Mahogany Zone (see Figure 2). The alluvial aquifer system occurs in the stream valley bottoms.

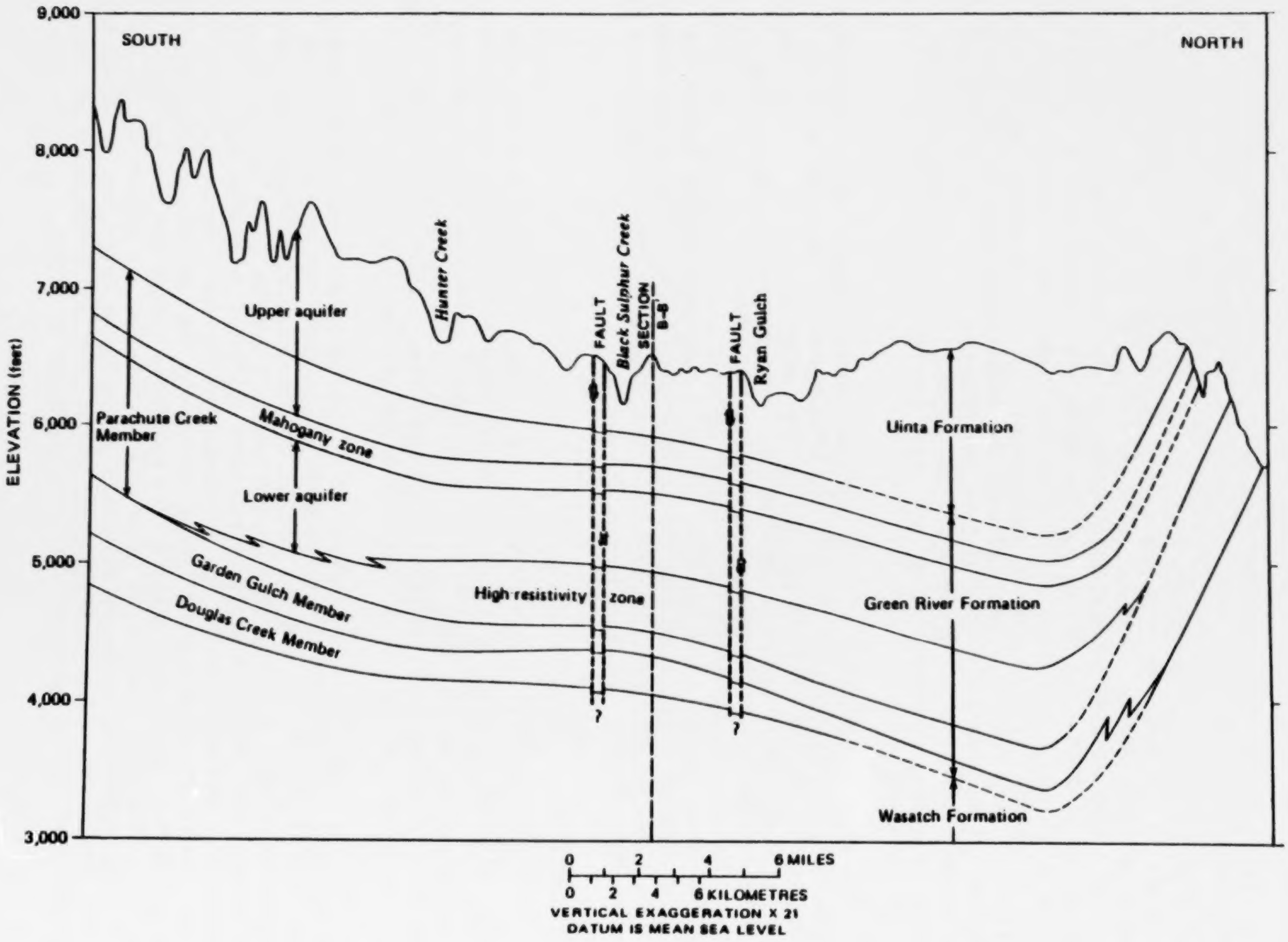

SOUTH
NORTH
ELEVATION (feet)
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Hunter Creek
FAULT
Black Sulphur Creek
SECTION B-B'
FAULT
Ryan Gulch
Upper aquifer
Parachute Creek Member
Mahogany zone
Lower aquifer
Garden Gulch Member
Douglas Creek Member
High resistivity zone
Uinta Formation
Green River Formation
Wasatch Formation
?
?
0 2 4 6 MILES
0 2 4 6 KILOMETRES
VERTICAL EXAGGERATION X 21
DATUM IS MEAN SEA LEVEL

Figure 2. Geologic section through Piceance Basin along north-south line between Tracts C-a and C-b (Weeks et al., 1974).

Lower Aquifer

The Lower Aquifer is bounded generally on the top by the Mahogany Zone and on the bottom by the shales of the Garden Gulch Member. Porosity is mostly secondary, resulting from fracturing and jointing of the marlstone and oil shale of the lower Parachute Creek Member. Porosity also results from the solution of the evaporite minerals in the saline section at the base of the Parachute Creek Member. Removal of these soluble minerals by groundwater has created a zone of high permeability (known as the leached zone) at the top of the saline section. The saline section below the leached zone still contains its original salts. Because of the high electrical resistivity of the salts, which characterizes this zone on geophysical logs, it is called the "high resistivity" (HR) zone. Inasmuch as both the high-kerogen-content oil shales and the saline minerals of the HR zone are rather ductile, the HR zone has experienced little fracturing and has a low permeability. Because of these characteristics, in the center of the basin the HR zone forms the lower confining stratum.

The fracture-solution of this confined aquifer results in heterogeneous hydraulic characteristics. In general, transmissivity increases with the soluble mineral content from the margins to the center of the basin. The degree of fracturing, resulting from deformation, increases toward the structural axis of the basin, and northwest along the axis. Weeks et al. (1974) estimated that the average transmissivity varies from 130 ft^2/day near the southeastern corner of the basin, to 670 ft^2/day in the area between Yellow and Piceance Creeks. They estimated the storage coefficient to be on the order of 10^{-4} and the specific yield to be 10^{-1}. Well yields of 200 to 400 gallons per minute (gpm) are typical.

Upper Aquifer

The Upper Aquifer is separated from the Lower Aquifer by the Mahogany Zone. Although no interaquifer response was observed during vertical permeability tests, Weeks et al. (1974) have concluded that considerable movement of water between the aquifers does occur. They base this conclusion on the fact that the water level in the two aquifers rarely differs by more than 100 feet over the 1,200-foot head drop of the two aquifers across the basin.

The Upper Aquifer zone is composed of the Parachute Creek Member above the Mahogany Zone and the Uinta Formation. The lower portion of the Uinta Formation is divided by numerous tongues of the Green River Formation. Although the primary porosity of the sandstones is greater than that of the marlstones, the sandstone porosity has been decreased by precipitates from groundwater, while fracturing has increased the permeability of the marlstones, which are more susceptible to fracturing than the Uinta sandstones. The sandstones, therefore, tend to form confining layers for the marlstone aquifers. The Upper Aquifer is generally confined but is unconfined in many locations, depending on the relationship of the water level and the lithology. Strata containing nahcolite ($NaHCO_3$) solution cavities, which occur in the southern part of the basin, should form transmissive layers.

The transmissivity (T) varies with saturated thickness, degree of fracturing, degree of solution, and location of wells with regard to fractures. Calculated T values range from 8 to 1,000 ft^2/day. The saturated thickness, degree of solution, and transmissivity increase toward the basin center. Weeks et al. (1974) considered representative values to be 70 ft^2/day around the rim, 130 ft^2/day in the area around the center, and 270 ft^2/day in the center.

Porosity ranges from 10 percent to 1 percent. It is highest in the center, where solution cavities are present, and least around the edges. The calculated storage coefficient is on the order of 10^{-3}, indicating confined conditions. The total storage is probably somewhat less than that in the Lower Aquifer due to lower saturated thickness and porosity.

Since the difference in water level between the two aquifers is rarely more than 100 feet, the potentiometric map of either the Upper or Lower Aquifer should not differ greatly. The potentiometric configuration is determined by the transmissivity distribution and the recharge and discharge characteristics. Recharge occurs around the rim of the basin, the gradual infiltration of snowmelt in the spring probably being the major source. The downward potential difference between the two aquifers around the rim of the basin indicates that most of the recharge is to the Upper Aquifer and that the Lower Aquifer is recharged by leakage from the Upper Aquifer through the Mahogany Zone. The water migrates toward the center of the basin, where it discharges to Piceance and Yellow Creeks at some locations. Here, the head of the Lower Aquifer is higher than the Upper, and Lower Aquifer discharge is through the Upper Aquifer.

Alluvial Aquifers

Alluvial sediments line most of the major stream valleys and are usually saturated at their base. They are thickest along Piceance and Yellow Creeks. Near the confluence with the White River, there may be 100 feet or more saturated alluvium underlying Piceance Creek. All of these aquifers follow the slope of their stream valleys. They are recharged in their upper reaches from streams and from snowmelt. In the lower sections, they are recharged from the deep aquifers and, in turn, discharge to the streams, maintaining the base flow.

The hydraulic conductivity of these unconsolidated alluvial deposits is high, reflected in transmissivities of 2,700 to 20,000 ft^2/day. Their unconsolidated nature also results in high specific yields, on the order of 20 percent. In spite of these favorable aquifer parameters, the alluvial aquifers are not desirable areas for large-scale water development because of the small total storage and boundary effects created by the aquifer morphology. In addition, withdrawal from the aquifers is sure to affect the stream base flow adversely, and with it agricultural interests, wildlife habitat, and existing water rights allocations.

GEOPHYSICAL METHODS

Phase I study efforts are documented in Slawson (1980b) and summarize geophysical methods that may be appropriate in defining the hydrogeologic characteristics in oil shale environments. This comprehensive review includes a wide range of geophysical well-logging techniques available through major logging companies. The utility of these geophysical tools for defining hydraulic properties in typical oil shale stratigraphy was not addressed in the Phase I study. This appraisal was conducted as part of the following Phase II efforts.

Suites of geophysical logs run during the post-leasing exploration studies on the Federal oil shale tracts in the Piceance Basin have been reviewed. Log suites for oil shale Tracts C-a and C-b are given in Tables 2 and 3, respectively. These tables show that while similar suites of logs are run on both of the Colorado tracts, specific logs are emphasized. For example, the engineering production (spinner) logs perform well and are commonly run on Tract C-a but seldom, if ever, on Tract C-b. Sonic logs are used extensively on Tract C-b but only infrequently used on Tract C-a, where three-dimensional velocity logs provide much of the same acoustic information. Use of alternate logging tools reflects, in part, individual log response, the information desired from their interpretation, the preference of the geophysical program coordinator, the logging service company selected to perform the work, and specific data-gathering requirements externally imposed on the exploration effort. Therefore, the most commonly run logs indicated in Tables 2 and 3 may not reflect the most appropriate suite for defining the hydrogeology in any one oil shale region.

Exploration studies on the Federal tracts are primarily interested in resource characterization. Defining the hydrogeologic framework, while important to the mine design, is initially of secondary importance. In the Phase II studies, Tempo reevaluated the geophysical exploration data with definition of the hydrogeologic framework as a primary focus. Following a review of these geophysical data and discussions with the major well-logging companies, a suite of logs has been selected to evaluate the hydrologic characteristics of test holes in an oil shale environment. This does not imply that a single suite of logs would be best suited for all boreholes. Unique borehole conditions must be dealt with on a site-specific basis. However, it is instructive to select a suite of geophysical logs and evaluate their effectiveness in defining the hydrogeologic framework in an oil shale environment. The following suite of logs has been selected for this purpose:

- Temperature log
- Caliper log
- Gamma-ray log
- Spinner log
- Radioactive tracer log
- 3-D velocity log
- Sonic/acoustic log
- Density log
- Electric log
- Seisviewer log.

TABLE 2. GEOPHYSICAL DATA COLLECTION, TRACT C-a

Geophysical logs	Well designations																
	Gulf-Standard core holes													Monitor holes			
	1	2-3	4-5	6	7	8	9	10	11	12	13	14	15	1	2	3	4
Schlumberger																	
Dual Induction Laterolog	X	X		X	X	X											
Compensated Neutron Formation Density	X	X		X	X	X											
Borehole Compensated Sonic-Gamma Ray		X		X	X	X											
Engineered Production (Spinner-Temp)				X		X											
Continuous Directional						X											
Birdwell																	
Electric			X				X	X	X	X	X	X	X	X	X	X	X
Gamma-Ray Density Neutron							X			X							
Three-Dimensional Velocity	X		X				X	X	X	X	X	X	X	X	X	X	X
Temperature	X	X	X				X	X	X	X	X	X	X	X	X	X	X
Spinner	X	X	X				X	X	X	X	X	X	X	X	X	X	X
Caliper (only)	X		X														
Seisviewer		X			X		X	X	X	X		X	X				
Nuclear (Gamma-Ray-Neutron)			X					X	X		X	X	X	X	X	X	X
Density	X		X														
Gamma-Ray Density								X	X		X	X	X	X	X	X	X
Continuous Directional Inclinometer													X				

TABLE 3. GEOPHYSICAL DATA COLLECTION, TRACT C-b

Geophysical logs	Well Designation																	
	AT-1	AT-1a	AT-1b	AT-1d	SG-1	SB-1a	SB-8	SB-9	SG-10	SG-11	SG-17	SG-18	SG-19	SG-20	SG-21	Cb-1	Cb-2	Cb-3
Schlumberger																		
Borehole, Compensated Sonic	X		X	X	X		X	X		X	X	X	X	X	X			
Laterolog	X		X	X	X		X	X		X	X	X	X		X			
Formation Density	X		X	X	X	X	X	X			X	X	X	X	X			
Nuclear Formation Density			X	X														
Temperature	X	X	X	X	X		X	X	X	X	X	X	X	X	X			
Birdwell																		
Three-Dimensional Velocity		X							X									
Electric		X							X									
Density		X							X									
Nuclear		X							X									
Caliper		X							X									
Temperature		X							X							X	X	X

A discussion of each of these logs has been developed for its specific use in defining hydraulic parameters of interest. As with all geophysical studies, conjunctive use of the individual logs is important in improving the accuracy of the interpretation. In addition, alternative data sources, e.g., water production tests and computer analogs that complement the geophysical record, are used wherever possible.

In compiling the information on current logging methods and sonde instrumentation, the logs from four major logging service companies were evaluated: Birdwell Division of Seismography Service Corporation, Schlumberger Well Services, Dresser Atlas, Inc., and Welex, A Halliburton Company. Data developed during the study was drawn from interviews with logging company personnel, information sheets and catalogs provided by the companies, and a review of logs run in wells on Federal Oil Shale Tracts C-a and C-b. Cost data for logging services was taken from the most current Rocky Mountain price schedules for the respective companies. Current prices may vary from those quoted in the text.

Temperature Log

Principle of Operation--

Temperature logs were run on nearly every test hole during exploration efforts on the Federal oil shale tracts. Temperature logs are made by passing a temperature electrode down a cased or an uncased hole. Temperature logs use a sonde with a resistance-type thermocouple or a wire calibrated to correlate resistance variations with temperature variations. In the former, a junction of two dissimilar metallic conductors is housed in a protective cage. An electromotive force is inducted at the junction when the conductors are maintained at different temperatures. This force is measured and recorded on strip charts or a magnetic tape at the surface. In the latter, the sonde uses a length of platinum wire that rapidly assumes the temperature of the borehole fluid. Variations in the temperature of the wire produce changes in resistance that are detected at a bridge circuit in the sonde. These signals are transmitted to a recording device at the surface.

The diameter of temperature sondes range from 1 to 3-5/8 inches and can be run down boreholes 2 to 20 inches in diameter. The temperature tool is used in a wide variety of borehole environments including water, mud, oil, or air.

Two passes of the temperature sonde should be recorded for each test hole studied. Both runs are made down the borehole. The first measurement should be made immediately after pulling the drill string and before natural circulation becomes established. The second run should be made at the end of the logging program. If the drilling fluids have been well circulated, the first run will provide an indication of the natural geothermal gradient, which can be used as a reference to compare anomalies from the second pass. Temperature anomalies show up at varying times after circulation has ceased, depending on the thermal conductivity of the formation penetrated, the flow rates within the well bore, and the diameter of the well.

On the oil shale tracts, temperature logs provide indications of fluid entry and exit from the well bore. In subsequent hydraulic studies they can be used to locate formation waters leaking through casing, which could create a contamination problem for water quality evaluations. During retorting, temperature logs can be used to detect and monitor excursion events.

Figure 3 is a computer plot of a typical temperature log from Federal Oil Shale Tract C-a. The log shows the effect of cooler formation water entering the well bore through small permeable zones between 580- and 850-foot depths. This water flows down the borehole, depressing the natural geothermal gradient to a depth of 1,420 feet. Below 1,420 feet, the sharp increase in fluid temperature suggests that the cooler waters have entered a "thief zone" and are no longer depressing the temperature of the borehole fluid.

Cost Data--

Costs for running temperature logs are computed based on per foot depth and operation charges. Minimum costs per test hole are based on 2,000 feet of logged hole. Current price schedules for the four major logging service companies are given in Table 4.

Evaluation--

Temperature logs are useful in providing indications of fluid movement in well bores and are essential in establishing baseline temperature data. Such information is utilized in subsequent pollutant migration evaluations or geochemical studies.

Temperature anomalies found on Tract C-a are primarily the result of well developed flow patterns from the Upper to the Lower Aquifer systems. These conditions are favorable for deducing hydraulic data from temperature logs. Tract C-b wells show less anomalous conditions, with many plots reflecting the natural geothermal gradient of the area. These logs are less instructive.

Caliper Log

Principle of Operation--

Caliper logs provide a continuous record of the variation in the diameter of the uncased drill hole. Several sonde configurations are available, e.g., two-, three-, four-, and six-arm devices. The average diameter of the hole is described by the tips of the arms of the device, which, when extended, contact the sides of the drill hole. The independent action of each arm, when grouped into pairs of opposed arms spaced 120 degrees apart, provides a direct measurement of up to three specific borehole diameters. These can be recorded simultaneously on a strip chart, with or without the calculated average hole diameter.

The caliper log is run by lowering the sonde to the bottom of the test section, actuating the arms, and pulling the tool out of the hole. It is commonly run with a temperature device or other logging tools.

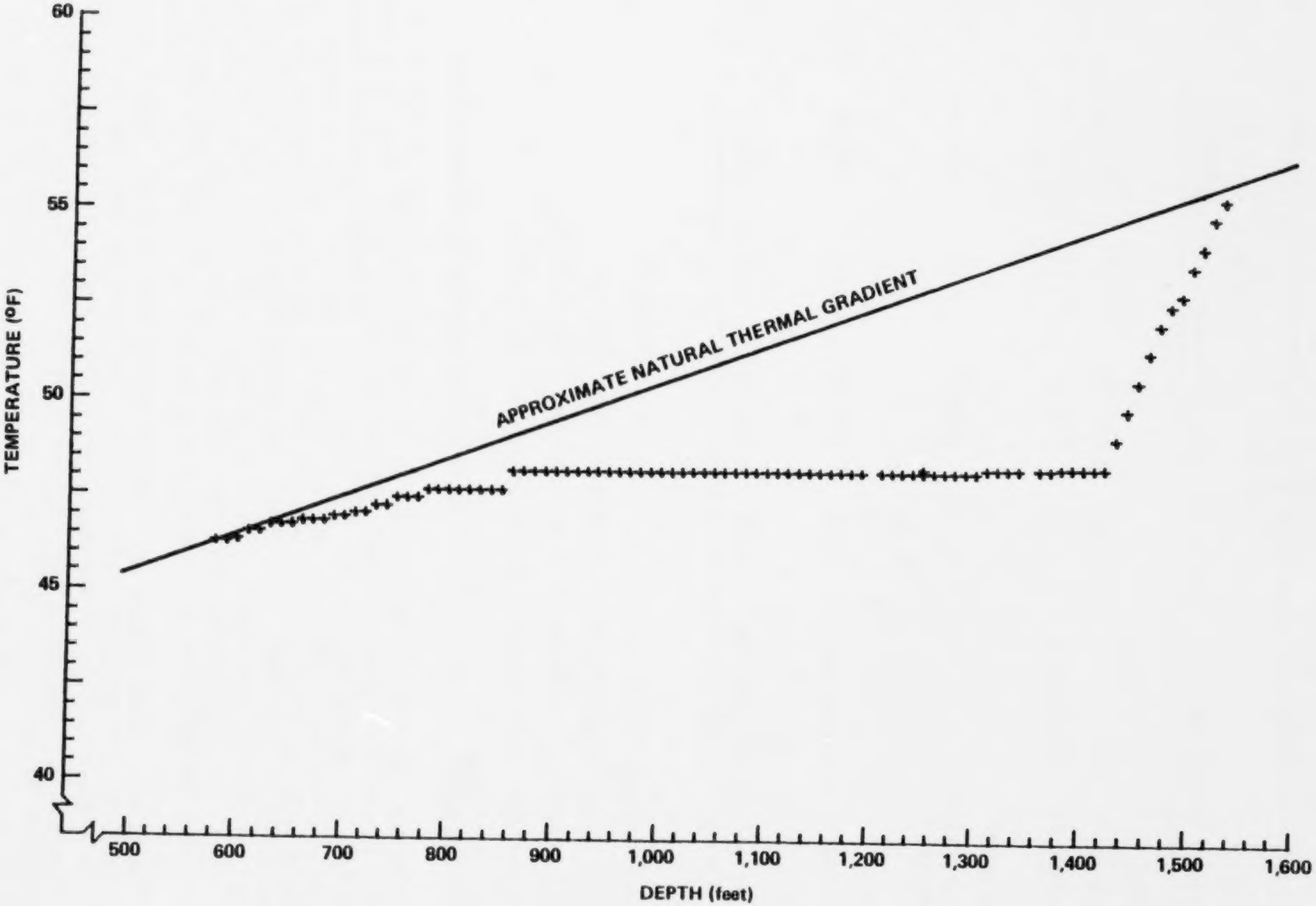


Figure 3. Computer plot of a typical temperature log from Tract C-a.

TABLE 4. COST SCHEDULE FOR TEMPERATURE LOGS (dollars)

Company/Service	Depth per foot	Depth minimum[a]	Operation per foot	Operation minimum[a]	Total minimum[a]
Birdwell[b]					
Temperature	0.22	440.00	0.19	380.00	820.00
Differential temperature	0.22	440.00	0.19	380.00	820.00
Schlumberger[c]					
High resolution temperature	0.26	520.00	0.21	420.00	940.00
Dresser Atlas[d]					
Differential temperature	0.28	560.00	---	750.00	1,310.00
Welex[e]					
Precision temperature log	0.25	500.00	0.20	400.00	900.00

Notes:

[a] All the service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[d] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[e] Welex Rocky Mountain Price Schedule, January 1980.

Caliper logs are primarily used to determine the volume of the drill hole and thus the annular space between the casing and the well. They are useful in identifying and permitting the correlation of nonround boreholes from well to well. In hydraulic testing, caliper logs are useful in the selection of competent beds required for setting packers. In general, determination of accurate borehole diameters is essential for quantitative interpretation of production engineering (spinner), electric, acoustic, density, and radiation logs. In oil shale stratigraphy, they are useful in locating soft, friable, or fractured zones, which are associated with porous and permeable beds.

The caliper sonde ranges in diameter from 1-5/8 to 3-5/8 inches for the three- and the six-arm tool, respectively. The smaller tool can be operated in a 3- to 30-inch-diameter borehole, while the larger tool requires a minimum hole diameter of 6 inches. They operate equally well in air-, mud-, oil-, and water-filled holes.

Cost Data--

Service company costs for running the caliper log is computed based on a per foot depth and operation charge. Minimum charges, based on 2,000 feet of logged hole, are given in Table 5.

TABLE 5. COST SCHEDULE FOR CALIPER LOGS (dollars)

	Depth		Operation		
Company/Service	per foot	minimum[a]	per foot	minimum[a]	Total minimum[a]
Birdwell[b]					
Caliper (3-arm)	0.22	440.00	0.19	380.00	820.00
Caliper (6-arm)	0.22	440.00	0.17	340.00	780.00
Schlumberger[c]					
Caliper (all)	0.26	520.00	0.21	420.00	940.00
Dresser Atlas[d]					
Caliper (4-arm)	0.26	520.00	0.21	420.00	940.00
Welex[e]					
Caliper (4-arm)	0.20	400.00	0.18	360.00	760.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[d] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[e] Welex Rocky Mountain Price Schedule, January 1980.

Evaluation--

In the dense, tight, oil-shale stratigraphy, fracture patterns control the secondary porosity and permeability within the formation. These fractured areas lead to zones of weakness in the borehole that may be subject to caving or raveling. Caliper logs are designed to detect these out-of-gage portions of the drill hole and therefore provide indirect information on porosity and permeability in oil shale environments. To evaluate this relationship, pump tests and spinner logs were compared to caliper logs. Below the static water level in the Federal oil shale tract wells, permeable zones correspond well with borehole enlargement due to caving (see Figure 5, page 41); i.e, lower permeabilities were found throughout in-gage sections of the holes, while large washouts, in general, corresponded to zones of higher permeability. Although the comparative evaluation is only qualitative, caliper logs are useful in directing hydraulic test programs to potential zones of permeability for further injection or production testing.

Gamma-Ray Log

Principle of Operation--

Gamma-ray logs measure emissions from natural radioactive materials found in all rocks. When the gamma rays emitted from the formation penetrate the sonde detector, usually a scintillometer, an electrical pulse is produced and transmitted to the surface recorder through electrical cables. The gamma-ray log is thus a curve relating depth to the intensity of natural radiation. Because clays and shales are considerably more radioactive than carbonates, i.e., limestone or dolomite, and sandstone, this geophysical tool is especially useful in "fingerprinting" lithologic sequences that are correlatable across well fields.

The gamma-ray sonde measures 1-5/8, 2-3/4, and 3-5/8 inches in diameter, depending on the company and tool selected, and can be used in a 2- to 15-inch-diameter borehole. The gamma-ray tool operates in all test hole environments and is effective in cased and uncased holes. In cased holes, it is combined with a casing collar locator for depth control while measuring complementary parameters and providing information on the cased lithology. In uncased holes, it can be combined with temperature, density, caliper, and other types of neutron logs.

Cost Data--

Service company costs for gamma-ray logging are divided into depth and operation charges with minimum fixed prices per hole. Price schedules for the four major logging companies are given in Table 6.

Evaluation--

The gamma-ray log is run separately or in combination with other logging tools on nearly every test hole on the Federal oil shale tracts. It is primarily used for lithologic correlation between tract wells and for depth control. Detailed core analysis for tract wells provides a better source for lithologic information, however, and supersedes the data from gamma-ray logs. The shale correction factor determined from the gamma-ray log is the key parameter in the petroleum industry but is not useful to the oil shale industry.

Spinner Log

Principle of Operation--

The spinner, or engineering production, log measures vertical flow in the borehole. The sonde consists of a propeller-type blade mounted to rotate about a vertical axis. Rotation of the blade is measured in counts per minute as a magnetic coupling passes a fixed reference point on the shaft, sending an

TABLE 6. COST SCHEDULE FOR GAMMA-RAY LOGS (dollars)

	Depth		Operation		Total
Company/Service	per foot	minimum[a]	per foot	minimum[a]	minimum[a]
Birdwell[b]	0.22	440.00	0.19	380.00	820.00
Schlumberger[c]	0.26	520.00	0.21	420.00	940.00
Dresser Atlas[d]	0.26	520.00	0.22	440.00	960.00
Welex[e]	0.20	400.00	0.18	360.00	760.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[d] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[e] Welex Rocky Mountain Price Schedule, January 1980.

electrical pulse to a surface recording station. Counts per minute are converted to flow past the sonde based on hole diameter, blade size, configuration etc. Measurements can be recorded with the sonde in a fixed position or while it is being lowered into or pulled out of the borehole. When recordings are made in the fixed position, the vertical flow rate in the hole must be sufficient to overcome the mechanical friction of the tool. This minimum flow rate will vary depending on the configuration and general condition of the sonde, the size of the blade, and the diameter and degree to which the hole is in gage. For example, experience has shown that a sonde with a 4-inch diameter blade inserted in a 5-inch hole requires a flow rate of approximately 5 ft/min to overcome mechanical friction, and give an accurate measurement in a fixed position. To minimize the effect of friction and measure small flow rates, the sonde is moved up and down the well at a constant rate.

Unlike temperature, caliper, or gamma-ray logs discussed earlier, the spinner log is a qualitative rather than a quantitative tool, requiring careful calibration for each test hole. Calibration charts can be developed by plotting counts per minute (cpm) versus logging speed. Figure 4 shows a calibration plot for a hypothetical 5-inch-diameter hole. Data for construction of the plot were gathered as follows:

- A gaged section of the borehole is selected, based on the caliper log

- Preliminary up- and down-hole spinner measurements are made to ensure that there is no vertical flow in the test section

- Three or more passes up and down the test section are made at varied logging speeds and the cpm readings recorded for each pass
- Counts per minute versus logging speed plot is constructed as shown in Figure 4.

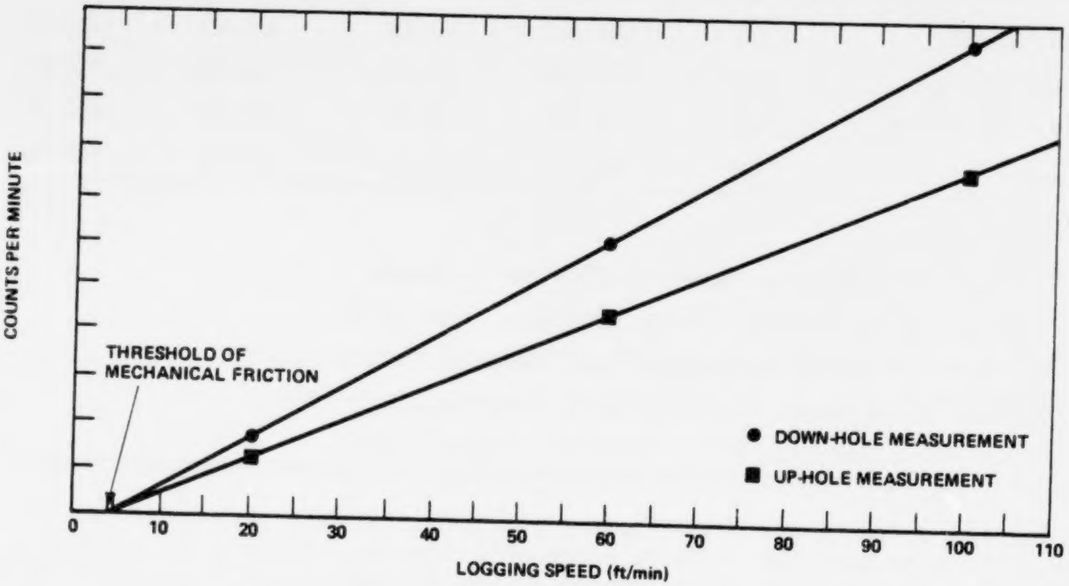


Figure 4. Spinner log calibration plot.

Calibration plots can also be made for specific out-of-gage borehole conditions if significant fluid production is suspected from a given stratigraphic horizon. In this case, a static test section with similar borehole characteristics can be used for construction of the calibration plot. In general, sections with high rugosity produce turbulent flow in the well bore and are extremely difficult to accurately calibrate.

Following construction of the calibration plot(s), a single run of the spinner tool should be sufficient to determine vertical flow velocity in the well. However, if the sonde is moved in the same direction and at approximately the same rate as the borehole, fluid mechanical friction of the tool will not be overcome and inaccurate flow measurements will result. This can be overcome by recording flow rates while moving the tool both up and down the hole at a constant rate. Comparison of the two velocity versus depth logs would show the velocity and direction of fluid movement more clearly.

Cost Data--

Costs for running a spinner survey are calculated based on the depth, operation expenses, and the number of passes that are made up and down the hole. These costs are given in Table 7.

TABLE 7. COST SCHEDULE FOR SPINNER SURVEYS (dollars)

Company/Service	Depth per foot	Depth minimum[a]	Operation per foot	Operation minimum[a]	Total minimum[a]
Birdwell[b]					
Spinner survey[c]	0.22	440.00	---	350.00	790.00
Schlumberger[d]					
Continuous flowmeter[e]	0.27	540.00	---	740.00	1,280.00
Second pass (in combination)	0.22	440.00	---	620.00	1,060.00
Dresser Atlas[f]					
Spinner Flolog	0.28	560.00	---	750.00	1,310.00
Additional runs	0.19	380.00	---	550.00	930.00
Welex[g]					
Spinner[h]	0.20	400.00	0.20	400.00	800.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Includes one recorded run down and one recorded run up. For additional recordings at different logging speeds, add $0.07/ft, $105.00 minimum.

[d] Schlumberger Rocky Mountain Price Schedule, October 1979.

[e] If more than one descent is made into a well with the same tool, each descent is considered a separate service and charged at the single service rate.

[f] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[g] Welex Rocky Mountain Price Schedule, January 1980

[h] Available in limited areas.

Evaluation--

Semiquantitative information can be developed from spinner surveys on a site-specific basis when calibration plots are carefully constructed. However, these data are dependent on the hydraulic head relationship and therefore on the dynamic flow characteristics of the permeable beds penetrated and interconnected by the well bore. For example, quantitative flow data can be derived from spinner logs run in boreholes that intercept two permeable zones with sufficiently different hydraulic heads to allow flow from one zone to another. This condition exists on Tract C-a, where water flows in response to potential differences from the upper to the lower permeable zones. The flow measured, however, does not necessarily reflect the true ability of an aquifer to produce or accept fluid from the borehole, but rather provides information on the existing flow system and provides lower limits of permeability and water production. Likewise, if two highly permeable beds are interconnected by a well and have nearly equal hydrostatic heads, the spinner survey provides little information on the aquifer hydraulics since no flow would occur in the well. This is perhaps one reason why spinner surveys are not as useful nor as commonly run on Tract C-b wells as on Tract C-a wells.

Radioactive Tracer Log

Principle of Operation--

The radioactive tracer sonde consists of an ejector that extrudes a short-lived radioactive source (I^{131}, I^{192}) into the borehole and one or two detecting elements. If a single-element sonde is used in logging, the radioactive source is emitted and the detecting element is moved through the source to determine its location in the borehole. After a short period of time, the detecting element is again moved up or down the hole to locate the source, and from the time-distance relationship the flow rate in the well can be calculated. With two detecting elements at fixed distances on the sonde, the source material is ejected and detected at the same time, and the tool does not have to be moved, thus reducing dispersion of the source and increasing the peakedness of the log trace, hence providing greater accuracy in locating the radioactive material in the well. With this type of tool, the source ejector can be located at either the top or bottom of the sonde to measure flow up or down the borehole.

The borehole instrument comes in 1- and 1-5/8-inch diameters and can be run in 1-1/2- to 12-inch-diameter wells. It will operate in all fluid-filled holes.

Cost Data--

Service charges for running radioactive tracer logs are given in Table 8. These include standard per foot and operating costs, as well as radioactive material ejector fees.

Evaluation--

The accuracy of the radioactive tracer log depends on the peakedness of the source-detection-versus-depth plot. This is primarily a function of knowing where the source is in the borehole. While tracer logs do not have the mechanical friction problems inherent in the spinner tool, extremely low borehole velocities provide time for diffusion of the source material and spread of the radiation-versus-depth plot, thereby limiting the accuracy of the measurements. Also, turbulence associated with higher flow rates tends to disperse the source material, especially in permeable areas where rugosity is often a significant characteristic of the borehole.

TABLE 8. COST SCHEDULE FOR RADIOACTIVE TRACER LOGS (dollars)

Company/Service	Depth per foot	Depth minimum[a]	Operation per foot	Operation minimum[a]	Total minimum[a]
Birdwell[b]					
Radioactive tracer profile[c]	0.22	440.00	0.19	380.00	820.00
Schlumberger[d]					
Radioactive tracer[e,f]	0.27	540.00	---	740.00	1,280.00
Second run	0.22	440.00	---	520.00	1,080.00
Dresser Atlas[g]					
Tracelog[h]	0.28	560.00	---	750.00	1,310.00
Additional runs	0.19	380.00	---	550.00	930.00
Welex[i]					
Radioactive tracer[j]	0.20	400.00	0.14	280.00	680.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Radioactive material ejector charge: $150.00 for the first ten stations and $0.11 per station thereafter.

[d] Schlumberger Rocky Mountain Price Schedule, October 1979.

[e] With radioactive tracer logging, an added charge of $112.00 per ejection of radioactive material is applied when a down-hole ejector tool is used.

[f] Radioactive material is charged at cost plus 10 percent handling charge.

[g] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[h] Tracer dump bailers $130.00 per run.

[i] Welex Rocky Mountain Price Schedule, January 1980.

[j] Radioactive material not included in price.

A significant disadvantage of the tracer log is the inherent danger in handling and the consequence of losing the radioactive source material (thereby contaminating the well). This is especially acute when working with shallow-water supply wells or in areas where groundwater may be transmitted directly into underground mine works. Attempts have been made to minimize this problem by using radioactive substances with a relatively short half-life (I^{131} half-life = 8 days). In general, the potential danger versus the qualitative or semiquantitative information gained does not warrant the use of radioactive tracer logs in groundwater wells.

Laboratory or supplier preparation of the source material requires time, which can result in delays in the field. If this method is used, careful planning must be made to coordinate drilling schedules and running other logs.

Three-Dimensional Velocity Log

Principle of Operation--

Birdwell's single-receiver velocity sonde provides a record of the complete acoustic wave train as propagated along the fluid-borehole boundary of the well. The total wave train is displayed as variable density, black lines (legs) on a strip chart and includes the compressional, shear, and boundary waves. The sonde contains a magnetostrictive-type transmitting transducer that generates pulses at a rate of 20 per minute. The ceramic receiving transducer (a barium titanate crystal) converts the signals transmitted along the borehole to electrical impulses that are transmitted to a receiver at the surface and recorded.

The three-dimensional (3-D) velocity log is used in fracture studies, porosity determinations, cement bond evaluations, and in the study of dynamically determined elastic properties of rocks. In the latter, compressional and shear waves are used in the calculation of elastic moduli (shear, bulk, and Young's) and in determining Poisson's ratio. Elastic properties are useful in oil shale mine design and are also used extensively in other types of construction projects.

The sonde diameter varies from 1-3/4 to 3-3/4 inches and can be utilized in test holes from 3 to 18 inches in diameter. The tool requires a fluid formation boundary to transmit the acoustic wave train; water, mud, or oil mediums are acceptable.

Cost Data--

Service company costs for running 3-D velocity logs, or equivalent, are given in Table 9. Welex's fracture-finder microseismogram log provides formation information similar to Birdwell's 3-D velocity log. The cement bond/variable density log is Schlumberger's closest equivalent to the 3-D velocity log, but is specialized to determine the effectiveness of the cement seal in the casing-formation annulus and does not give comparable information. Dresser Atlas did not have a 3-D velocity log listed in its wireline service catalog.

Evaluation--

The 3-D velocity log provides valuable information on the elastic properties of rocks useful in mine design, and it is one of the few down-hole geophysical tools that provides a complete record of the acoustic wave train. However, in hydrology studies where porosity determinations are of primary importance, shear and boundary waves are not required. Variation in the

TABLE 9. COST SCHEDULE FOR 3-D VELOCITY LOGS (dollars)

	Depth		Operation		Total
Company/Service	per foot	minimum[a]	per foot	minimum[a]	minimum[a]
Birdwell[b]					
3-D velocity	0.29	580.00	0.25	500.00	1,080.00
Schlumberger[c]					
Cement bond/ variable density log	0.26	520.00	0.25	500.00	1,020.00
Welex[d]					
Fracture-finder Microseismogram log	0.27	540.00	0.23	460.00	1,000.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[e] Welex Rocky Mountain Price Schedule, January 1980.

interval transit time (Δt) of the compressional wave along the fluid-formation boundary provides the Δt value needed for porosity calculations. This travel time is a function of the rock and fluid properties in the borehole as well as the distance between the detectors. While the detector spacing in the sonde is fixed, the overall travel distance depends on the rugosity of the well bore. Smooth in-gage sections produce the shortest travel distances, while washouts or out-of-gage sections produce longer travel distances for a fixed set of receivers. The 3-D velocity log is not designed to compensate for this variation in travel distance and thus will introduce error into the Δt values and hence the porosity measurements calculated from these data. Therefore, in hydrology studies where porosity determinations are of primary interest, specially designed, compensated acoustic logs are recommended. This type of log is discussed below.

Acoustic Log

Principle of Operation--

The acoustic, or sonic, sonde consists of two sections. The upper section houses the electronic equipment necessary to control and activate the transmitting transducers that convert electrical impulses to acoustic pulses. Pressure waves created by the acoustic pulses radiate out from the sonde, are refracted through the formation, and return to the borehole instrument through the drilling fluid. The lower section contains both transmitting and receiving transducer component in a rigid, slotted metal sleeve. The sleeve is specially designed to separate acoustic energy transmitted through the instrument from signals received from the formation. For a single compensated sampling point, Δt is computed through selectively combined time signals from the receiving transducer array.

Changes in borehole diameter and misalignment of the instrument axis have signification implications on the accuracy of the acoustic sonde. For limited variations in borehole diameter or instrument misalignment, multiple transducer arrays have been developed to ensure accurate measurement recordings. This is accomplished through a surface panel capable of combining and averaging signals from two transducer arrays, inverted with respect to one another, for the same borehole interval.

The diameter of the sonde varies from 3-3/8 to 3-3/4 inches, depending on the tool selected. It is run in fluid-filled, open holes ranging from 6 to 18 inches in diameter at logging speeds of 30 to 80 ft/min.

Measurement of interval transit time is the primary purpose of the compensated acoustic log. Interval transit time may be used to determine porosity using the following equation:

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad , \tag{1}$$

where: ϕ is porosity (dimensionless)

Δt is interval transit time (μsec/ft)

Δt_{ma} is matrix interval transit time (μsec/ft)

Δ_f is fluid interval transit time (μsec/ft).

Service companies provide automatically computed and recorded porosity values given the desired fixed matrix and fluid velocities using the above relationship. The utility of the porosity measurements for hydrology studies and their correlation to permeable zones has been evaluated for a test section located on Federal Oil Shale Tract C-b.

The test zone includes 800 feet of oil shale stratigraphy penetrated by Tract C-b Well 32x-12 (see Figure 5). Water production from pump and spinner tests and borehole enlargements from caliper logs are presented with a porosity analog developed from Equation 1. The test zone was selected for its geophysical logs, varied lithology, and water production data. Stratigraphic features included in the section are as follows:

- 220 feet at the base of the Uinta Formation (±800 to 1,020 feet)
- Top of Parachute Creek (±1,020 feet)
- Four Senators Zone (±1,100 feet)

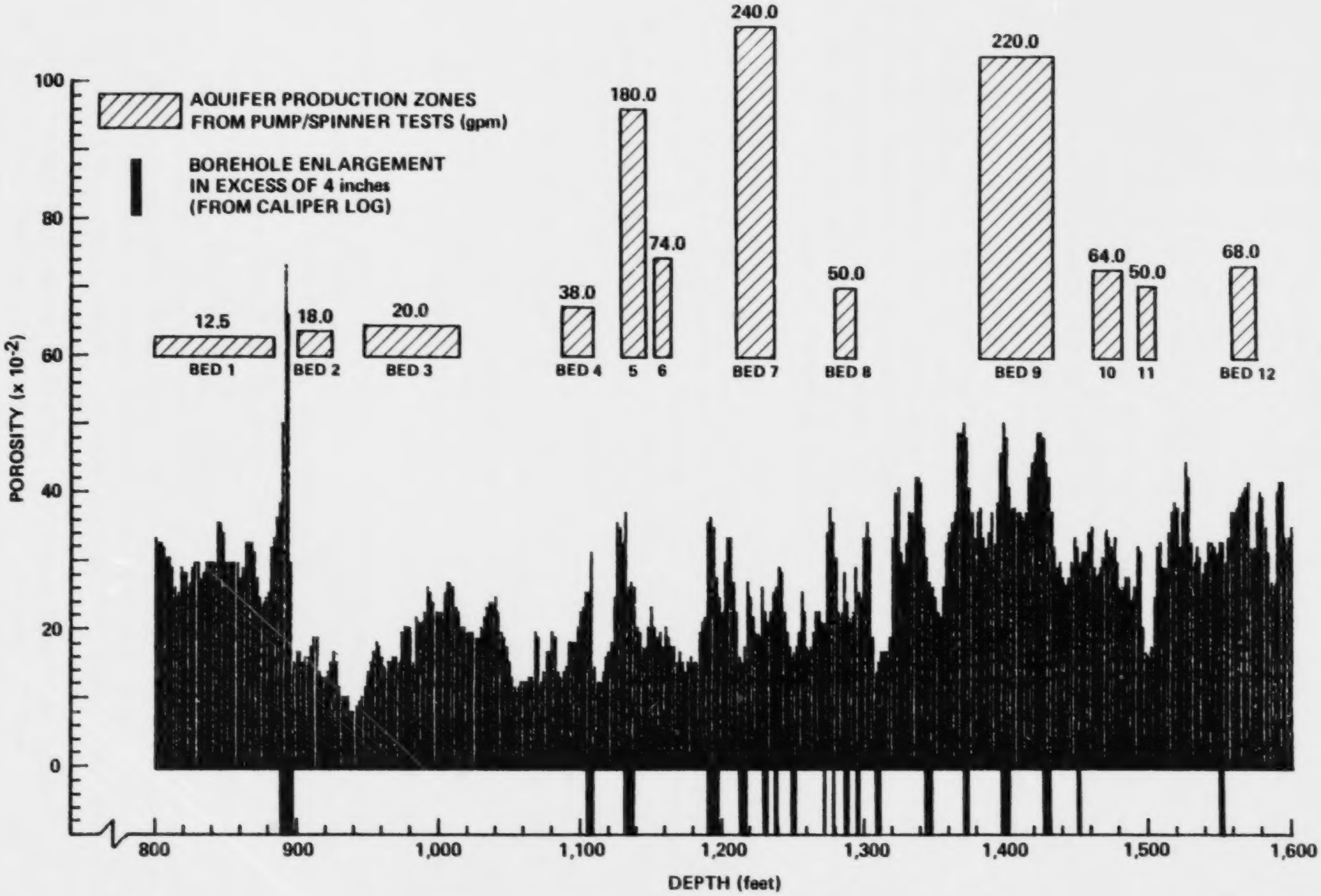


Figure 5. Acoustic porosity analog and aquifer production zones for Tract C-b Well 32x-12.

- A-groove (±1,310 feet)
- Mahogany Zone (±1,400 feet)
- B-groove (±1,500 feet)
- Top part of R-6 Zone (±1,520 to 1,600 feet).

The porosity analog was developed from interval transit times taken from a Birdwell acoustic/borehole compensated log. The matrix interval transit time, taken from a graph of oil shale yield versus time developed by Birdwell, was set at 59 µsec/ft. Varying this parameter shifted the porosity axis (y-axis of the analog plot) but did not affect the relative magnitude of the porosity values. As can be seen in Equation 1, decreasing the matrix interval transit time will increase the porosity values when the other variables are held constant. The fluid interval transit time was set at 198 µsec/ft, an average value for fluids in oil shale test holes (oral communication with Mr. Asher Atkinson, Rocky Mountain Regional Manager for Birdwell Division). Increasing this parameter increases the denominator of the porosity equation, thus decreasing porosity values. Again, the shift in the axis does not affect the relative magnitude of the calculated porosity values.

Porosity values for the upper part of the test hole (between 400 and 800 feet; not shown on Figure 5) are uniform, averaging about 32 percent void ratio. These values appear to be high and are probably the result of a relatively low average Δt_{ma} value (held constant in Equation 1) for the Uinta Formation and the uniform, but oversized, borehole diameter. Below a depth of 880 feet, the caliper log shows the hole returning to gage (10-3/4 inches) and more variation in the porosity is observed. The prominent spike between Beds 1 and 2 is a washout of probable high porosity that was too large for accurate measurements, even with the averaging of signals from the transducer arrays. Narrower washout features (shown at the base of the y-axis) are for the most part eliminated from the porosity analog through transit-time signal averaging. Some of the features may represent solution cavities that cause high rugosity, which, with a continuous matrix framework, will transmit the acoustic energy as if through solid rock.

The correlation between permeable production zones and the porosity analog is complex. High water production from Bed 9 (between 1,393 and 1,450 feet) corresponds to a relatively wide band of high porosity values. The apparent porosity appears to be a combination of the rich oil shale beds (Mahogany Zone) and true secondary porosity created by solution breccia zones and fracture breccia, or "rubble" beds. The rich grades of oil shale tend to increase Δt, thus increasing the calculated porosity when Δt_{ma} remains constant. The three prominent porosity peaks within and slightly above Bed 9 correspond to washout zones on the caliper log and solution or breccia horizons on the lithologic log. Here, partings and solution cavities must contribute significantly to the void space in the rock matrix. Based solely on the relatively low porosity calculations, Bed 7 (between 1,222 and 1,247 feet) cannot be expected to produce the large quantities of water shown in Figure 5. The caliper log for Bed 7, however, shows three narrow washout zones, two corresponding to fracture "rubble" breccia horizons. In addition, the rock fracture and partings log shows a large number of major fractures within the bed. In this case, the permeability may be created by partings that are not large enough to significantly increase the void ratio of the matrix, or the partings may be oriented vertically and do not influence the speed of the acoustic waves. An alternate explanation could be that solution cavities are interconnected through an otherwise consolidated matrix. Bed 5 (between 1,135 and 1,145 feet) is producing from a narrow, highly fractured zone, with no core recovery found within the bed (represented by a spike in the porosity analog).

In general, the porosity analog shows high porosity values for the entire test section. This is probably due to the relatively low fixed matrix travel time for the varying grades of oil shale.

Cost Data--

Service company price schedules for running acoustic/sonic logs are given in Table 10. These costs are broken down into depth and operation charges.

Evaluation--

Porosity calculations from acoustic/sonic log interval transit times should be considered semiquantitative and used with an understanding of the parameters that interact to yield these data. The matrix interval transit time, held constant in constructing the porosity analog, can vary significantly with a change in oil shale yield from 10 to 35 gal/ton. This could cause a large error in the porosity calculation. Fluid interval transit time, held constant in Equation 1, will also vary with temperature, pressure, and amount of dissolved salts in the well fluid. However, these parameters produce less change in Δt_f in shallow borehole conditions and can generally be disregarded. In addition, the interval transit time can be affected by extreme borehole rugosity, as shown in Figure 5, even with the compensating receiving arrays of the acoustic sonde.

Of the parameters discussed above, changes in the grade of the oil shale are believed to produce the largest single variation in the computed porosity. Utilizing Fischer analysis to determine oil shale grade, and hence an approximate interval transit time, more quantitative porosity calculations can be made by varying Δt_{ma} with depth in Equation 1. Unfortunately, Fischer analyses for Well 32x-12 and most of the other test holes on the Federal tracts are confidential information and therefore were not available for study. It may be of interest to tract developers who have access to Fischer analysis to calculate porosity values varying Δt_{ma} with depth and compare this analog with water production in the well bore.

Density Log

Principle of Operation--

The density sonde consists of a gamma-ray source (usually cesium-137), two gamma-ray detectors, a caliper arm used to force the source/detector against the well bore, and electronic equipment required to transmit data to

TABLE 10. COST SCHEDULE FOR ACOUSTIC/SONIC LOGS (dollars)

Company/Service	Depth per foot	Depth minimum[a]	Operation per foot	Operation minimum[a]	Total minimum[a]
Birdwell[b]					
Acoustic/borehole compensated	0.29	580.00	0.25	500.00	1,080.00
Schlumberger[c]					
Sonic/borehole compensated	0.29	580.00	0.27	540.00	1,120.00
Dresser Atlas[d]					
Borehole compensated acoustilog-caliper	0.20	580.00	0.27	540.00	1,120.00
Welex[e]					
Compensated acoustic velocity	0.27	540.00	0.23	460.00	1,000.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[d] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[e] Welex Rocky Mountain Price Schedule, January 1980.

the surface panel. The source and detectors are shielded with heavy metal to ensure that the signal received is primarily from gamma rays that have traveled through the formation.

The count rate of gamma rays reaching the detectors is inversely proportional to the number of electrons per unit volume of the formation between the source and detectors. Therefore, the number of gamma rays per second reaching the detector is a function of the bulk density of the formation. A compensating effect of the sonde is the short and long spacing of the detector relative to the gamma-ray source, which reduces error caused by borehole rugosity, and a perturbation created by the change in density of the mud cake relative to the formation on the borehole wall.

The density log is primarily used to measure formation porosity. Logging service companies provide automatically computed and recorded porosity values from the compensated bulk density measurements. The relationship used to calculate porosity is as follows:

$$\phi = \frac{\ell_{ma} - \ell_b}{\ell_{ma} - \ell_p} \qquad (2)$$

where: ϕ is the porosity

ℓ_{ma} is the density of the formation matrix

ℓ_b is the bulk density measured by the logging tool

ℓ_p is the density of the formation interstitial fluid.

The utility of these porosity data and their correlation with permeable zones has been evaluated for a test section on Tract C-b Well 32x-12. This is the same section used to study calculated porosity values from the acoustic log.

Figure 6 shows the density porosity analog, aquifer production zones from pump/spinner tests, and borehole enlargements (washouts) from a caliper log in a format similar to Figure 5. This analog was developed using 2.52 gm/cc as the fixed matrix density and 1.00 gm/cc for the interstitial fluid density. The matrix density was derived from a graph developed by Birdwell relating oil shale yield in gallons per ton to matrix density in grams per cubic centimeters. The value of 2.52 gm/cc represents the extrapolated density of oil shale rock with a yield of zero gallons per ton. This is an equivalent density value to the matrix transit time used in computation of the acoustic porosity analog. Like the acoustic porosity analog, varying the numerical value of the matrix density does not alter the relative calculated porosity values, it simply shifts the porosity (y-axis) of the plot, other parameters held constant. Thus, increasing the matrix density will increase the porosity for a given bulk density reading.

In general, the density-derived porosity analog appears to reflect secondary porosity and its associated permeability more closely than the acoustic analog. Nearly all the poorly consolidated fracture/rubble zones, indicated by washouts on the caliper log, or zones of poor core recovery have been recorded as porosity peaks on the analog. These peaks correspond with beds of high water production and suggest alternate horizons that should be considered for inclusion in the permeability testing. For example, the prominent porosity peak beween Beds 8 and 9 (Figure 6) should have been included in a packer permeability test as it appears to have the potential of producing a significant quantity of water. Smaller, less prominent peaks between Beds 1 and 2 and Beds 11 and 12 should also have been considered for inclusion in the hydrology testing program.

In the dense, tight, oil shale rocks, secondary porosity (vuggy solution cavities or fraction zones) produces the principal groundwater flowpaths. In sections where secondary porosity exists, a density or neutron porosity analog should read higher than the acoustic porosity analog. The difference between the two porosity values has been defined as the secondary porosity index (SPI). This index exists because acoustic logs ignore vuggy solution porosity since a continuous path for the acoustic energy exists through the solid formation matrix. In comparison, density or neutron logs respond to bulk-volume

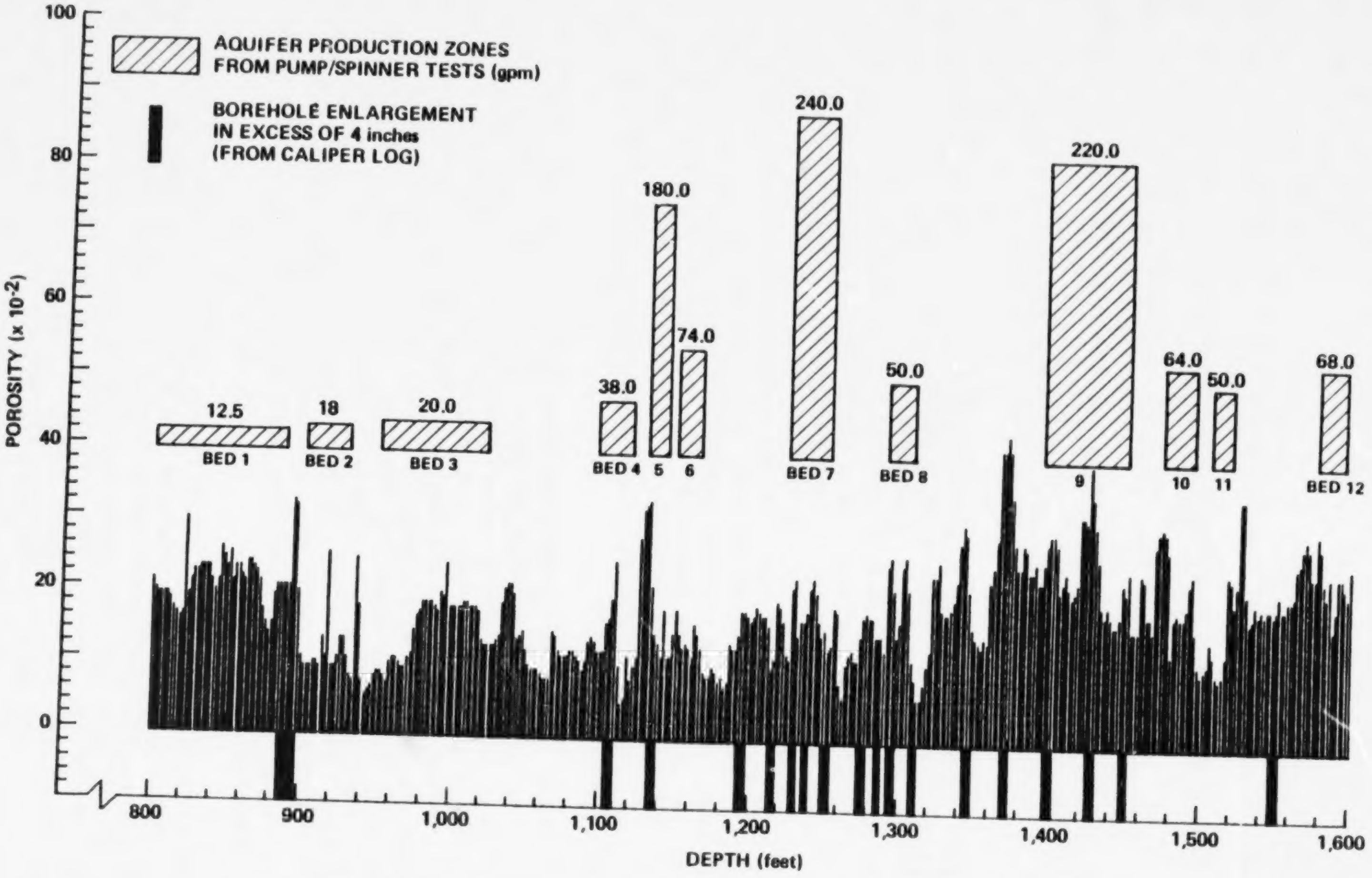


Figure 6. Density porosity analog and aquifer production zones for Tract C-b Well 32x-12.

porosity. For secondary fracture porosity, the bulk-volume porosity added by the fracture system is small unless the zone is extensively rubblized, and the SPI will not provide useful information.

Porosity analogs (density and acoustic) for the test section in Well 32x-12 were computed with equivalent matrix characteristics so that the SPI could be evaluated. Comparison of Figures 5 and 6 shows that the acoustic porosity values are, in general, higher than the density porosity values. This relationship is more clearly shown in Figure 7 for Section 1 of a Birdwell elastic property log for Well 32x-12. The computed porosity values in Figure 7 will not correspond with Figures 5 and 6 because porosity in Figure 7 was calculated with apparent sandstone unit parameters as follows: matrix density, 2.62 gm/cc; fluid density 1.00 gm/cc; matrix interval transit time, 192 μsec/ft. However, the same general trends occur when the acoustic porosity is greater than the density porosity. This is an anomalous situation, for porosity calculations from density logs should represent the total matrix porosity and be greater than the acoustic porosity. It appears that for the rich oil shale rock, the large volume of organic material included in the matrix increases the bulk density readings and thus reduces the calculated porosity more than it affects the transit travel times used in the acoustic porosity determinations. Porosity from density measurements are larger than acoustic porosity in breccia zones (washouts on the caliper log), where secondary porosity is extremely high (see Figure 7). Hence, the SPI values (shaded areas in Figure 7) correspond to production test beds rather well and suggest where additional packer permeable tests might have been run, i.e., shaded zone above Bed 7.

A porosity analog was computed from bulk density measurements taken in Tract C-a, Well CE-705A. Apparent limestone unit parameters (ℓ_{ma} equal to 2.69 gm/cc, and ℓ_f equal to 1.00 gm/cc) were used in the porosity calculations. Figure 8 shows the resulting analog along with a spinner survey for the same section. The spinner survey was constructed so that the step-like incremental change in water production or intake was positioned at the first increase in slope of the log trace for water production and at the base of the slope for thief zones. For this log presentation, water production zones will be located down-hole from the step-wise increase in the spinner log or up-hole from a step-wise decrease, given the established flow direction down-hole. Qualitative evaluation of these logs shows a partial correlation between water production/thief beds and high porosity values. However, a nearly perfect correlation (except for Zone R-6) is found when porosity values are compared to rich oil shale zones shown at the base of the y-axis. Again, it is well known that the porosity analog is strongly influenced by oil shale grade.

Cost Data--

Cost information from four major logging companies that run formation density logs is given in Table 11.

Evaluation--

Bulk density measurements taken from the density log can be used directly for cross-correlation of wells or test holes throughout the exploration phase of an oil shale mine development program. Porosity analogs developed from the

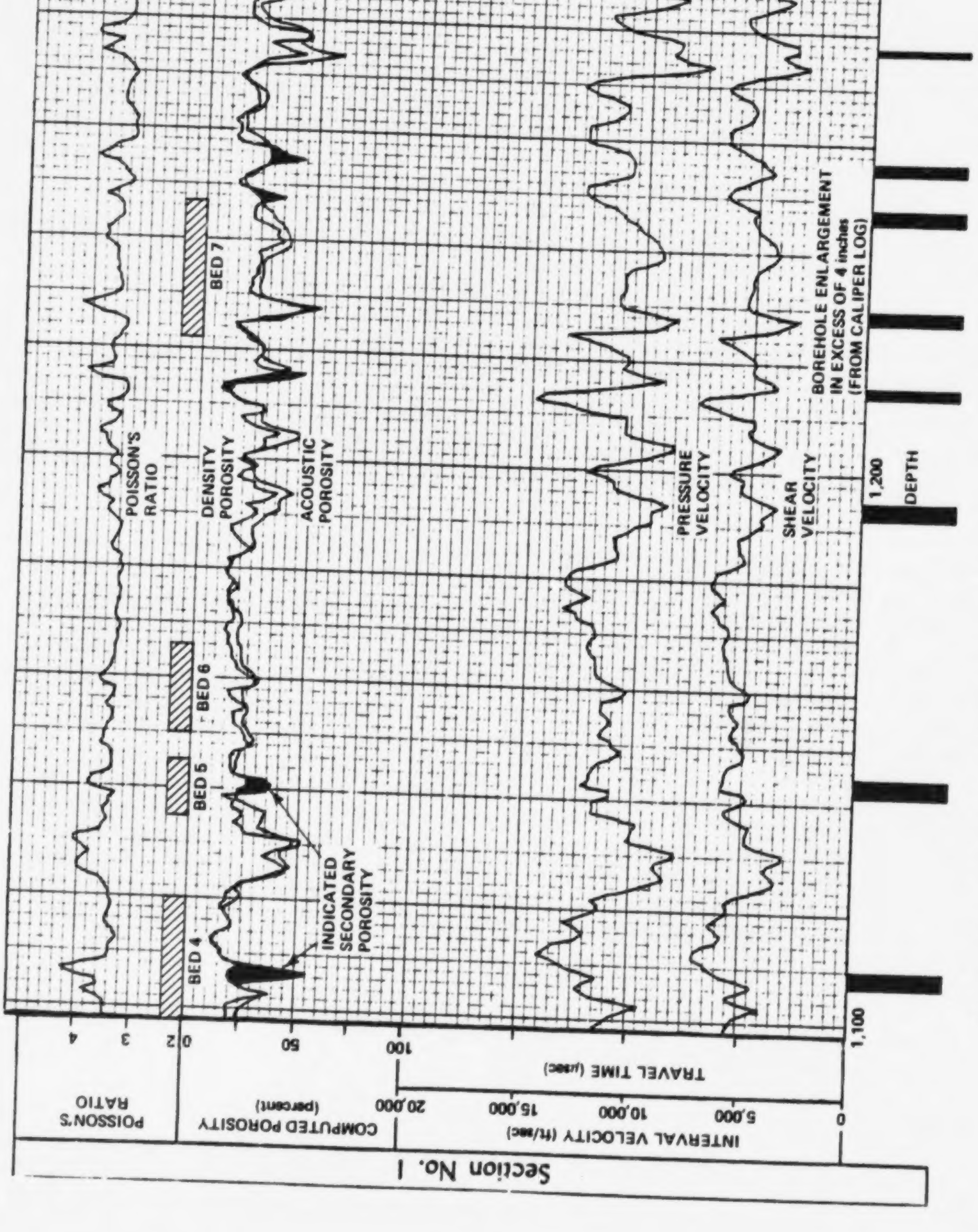


Figure 7. Birdwell elastic properties log for Well 32x-12, Tract C-b.

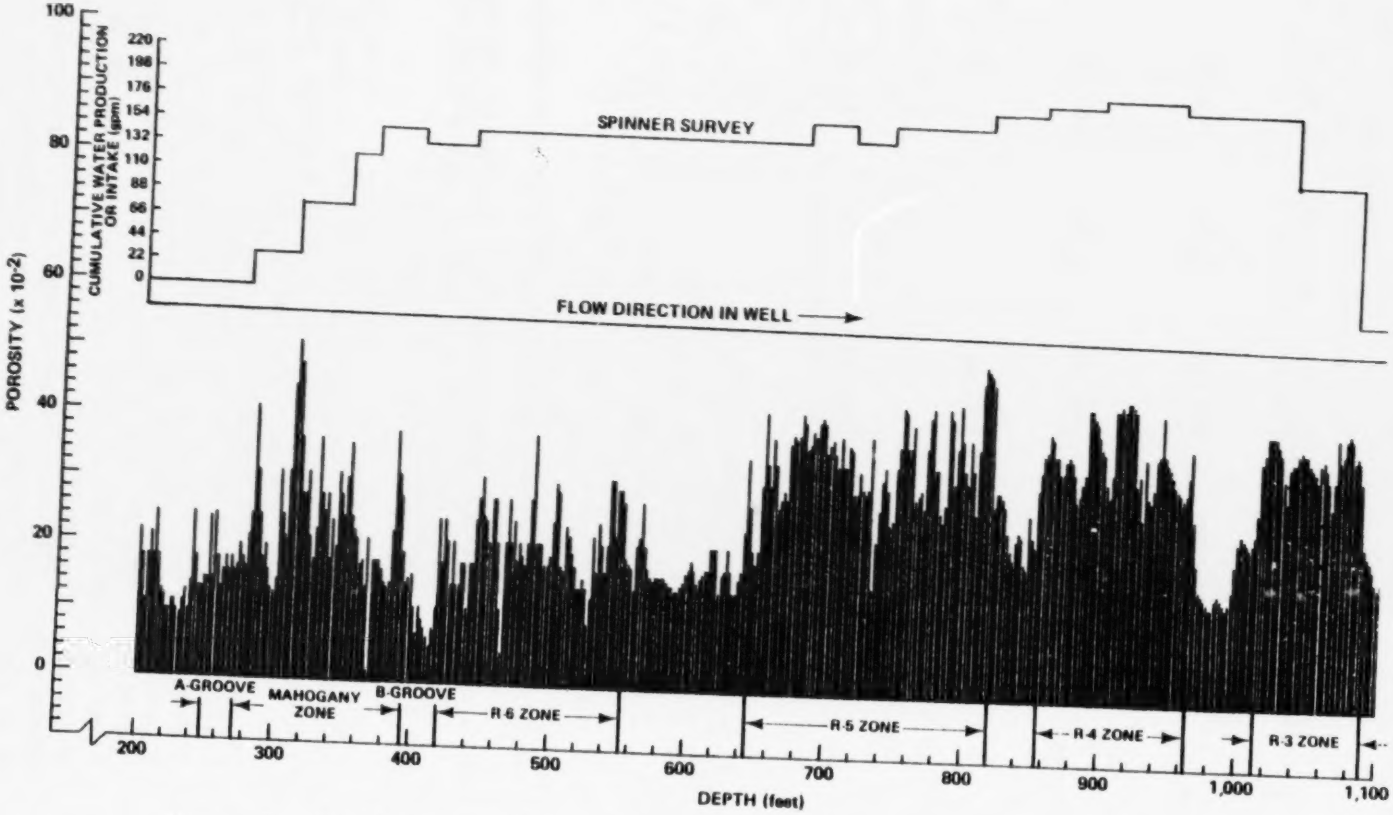


Figure 8. Density porosity analog and spinner survey for Tract C-a Well CE-705A.

TABLE 11. COST SCHEDULE FOR DENSITY LOGS (dollars)

Company/Service	Depth per foot	Depth minimum[a]	Operation per foot	Operation minimum[a]	Total minimum[a]
Birdwell[b]					
Density/borehole compensated	0.27	540.00	0.23	345.00	885.00
Schlumberger[c]					
Formation density	0.29	580.00	0.27	540.00	1,120.00
Dresser Atlas[d]					
Compensated densilog-caliper	0.29	580.00	0.27	540.00	1,120.00
Welex[e]					
Compensated density log	0.27	540.00	0.23	460.00	1,000.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[d] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[e] Welex Rocky Mountain Price Schedule, January 1980.

density logs can be used to define the hydrogeologic framework; however, these data should be considered semiquantitative and used in conjunction with other geophysical logs, i.e., caliper, fracture, lithologic, etc.

In constructing porosity analogs from density data, oil shale grade will affect the porosity calculations. This is shown in Figure 8, where rich oil shale zones correspond to high porosity values, and is a direct result of the method used in constructing the analog. The matrix density, held constant in computer routines used by logging companies to construct porosity analogs, can vary 19 percent with a change in oil shale grade from 10 to 35 gal/ton. This would produce a change in porosity of up to 25 percent if values of the other parameters in Equation 2 are held constant, reflecting, in part, a real change in the primary porosity of the oil shale with pore spaces filled with less dense organic material. This type of primary porosity would not serve as a conduit for groundwater and therefore would not correlate with permeable zones important to hydrogeologic studies. In an attempt to illuminate the effect of oil shale grade on porosity calculations, another analog was developed for the same test section in Well CE-705A and is shown in Figure 9. This porosity analog was constructed with bulk density measurements taken from the same

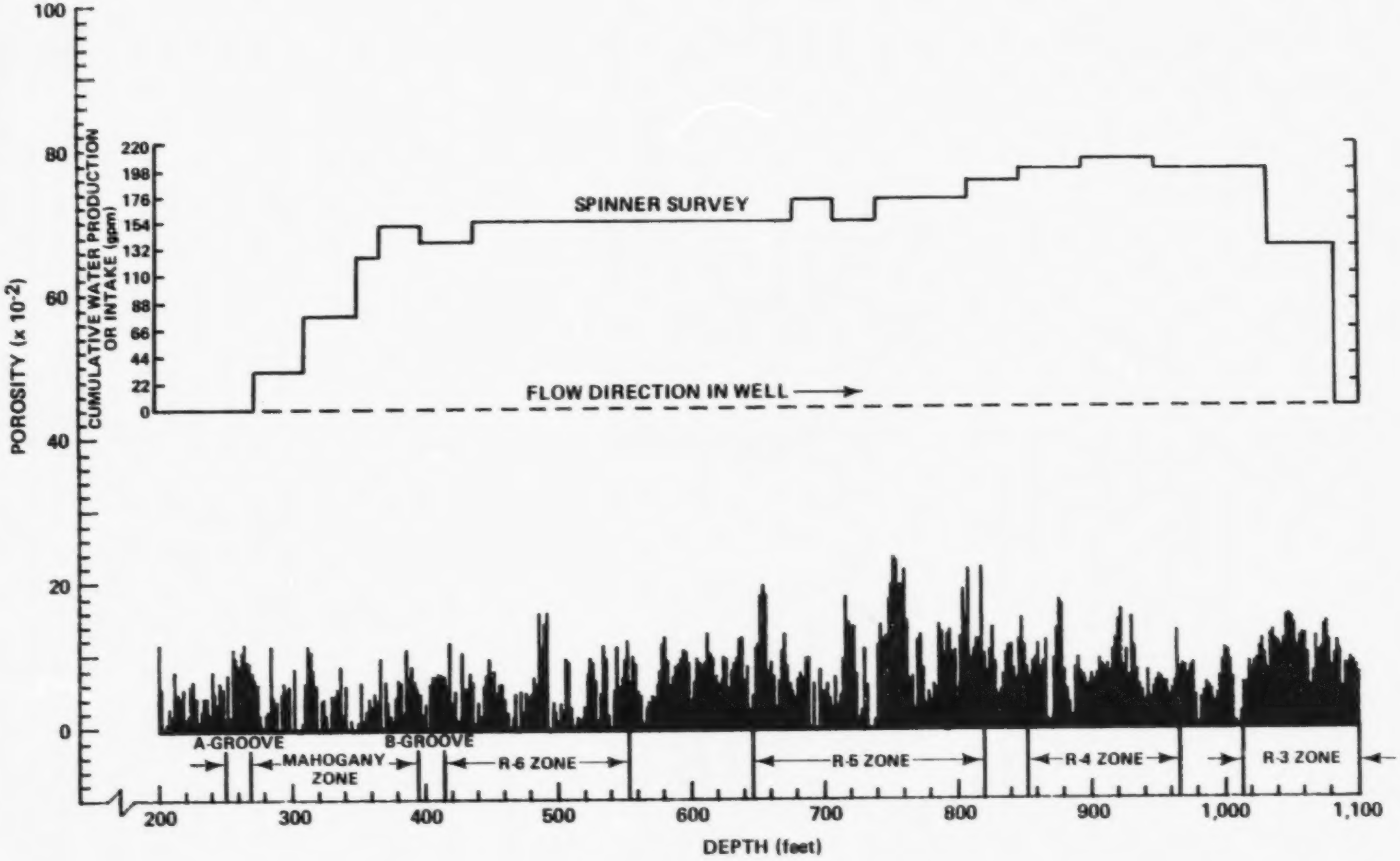


Figure 9. Variable matrix density-porosity analog and spinner survey for Tract C-a Well CE-705A.

Birdwell density/borehole compensated log used to construct Figure 8. In Figure 9, matrix densities were varied with depth based on Fischer analysis and on the relationship of oil yield to specific gravities of Colorado oil shale developed from a nearby test hole on Tract C-a. A problem in constructing the analog developed in a few cases where bulk density measurements were found to be higher than corresponding matrix densities based on the Fischer analysis. In these cases, the numerator of Equation 2 became negative and negative porosity values resulted. These values were set equal to zero in the computer routine used to calculate the analog. An explanation for this phenomenon may lie in errors, nonrepresentative Fischer analysis (2-foot varied lithologic sections described by a single analysis), or calibration errors in the density log. In addition, a discrepancy was noted in the density values for the varying grades of oil shale. Birdwell plots shows density varying from 2.49 to 1.66 gm/cc with a corresponding change in oil shale grade from 2 to 80 gal/ton. A table developed by the Department of Energy shows density varying from 2.66 to 1.58 gm/cc for the same change in oil shale grade. This latter range of densities was used to set matrix values for construction of Figure 10.

Comparison of Figures 6, 7, and 8 with Figure 9 show marked differences. Figure 9 appears to provide a more realistic range of porosity values but shows little correlation with water production from the spinner log. The generally high porosity values correlating with rich oil shale zones have been eliminated, leaving isolated porosity peaks. Unfortunately, alternate logs instructive in evaluating these peaks (caliper, fracture, and lithologic, etc.) were not available for review; thus, the utility of Figure 9 could not be fully determined. In theory, porosity analogs developed by varying the matrix density to reflect the true lithologic conditions should provide a better measure of porosity and should lead to correlation methods to equate permeable and porous zones in the oil shale stratigraphy. Additional analogs should be developed to evaluate this tool in defining the hydrogeologic framework.

Electric Logs

Principle of Operation--

Electric logs measure the electrical properties of the formation and drilling fluids that penetrate the borehole wall. These properties include electric potential and resistivity or, conversely, conductivity. The electric log is primarily used for the construction and correlation of stratigraphic and structural cross sections and in delineating permeable beds.

Multiple-track log presentations, including measurements of electric potential and resistivity/conductivity, are commonly used. The dual-induction laterolog discussed here consists of a correlation log, including spontaneous potential, resistivity, and conductivity measurements on a log scale of 2 inches per 100 feet, and a detail log (5 inches per 100 feet) developed from deep- and medium-reading induction devices and a shallow-investigation, focused resistivity tool. The detail log is recorded on a logarithmic grid along with a standard spontaneous potential curve. Portions of the correlation and detail logs from Tract C-a Well CE-705A are shown in Figures 10 and 11, respectively. The three types of electric logs (spontaneous potential, induction, and focused current resistivity) are usually run simultaneously.

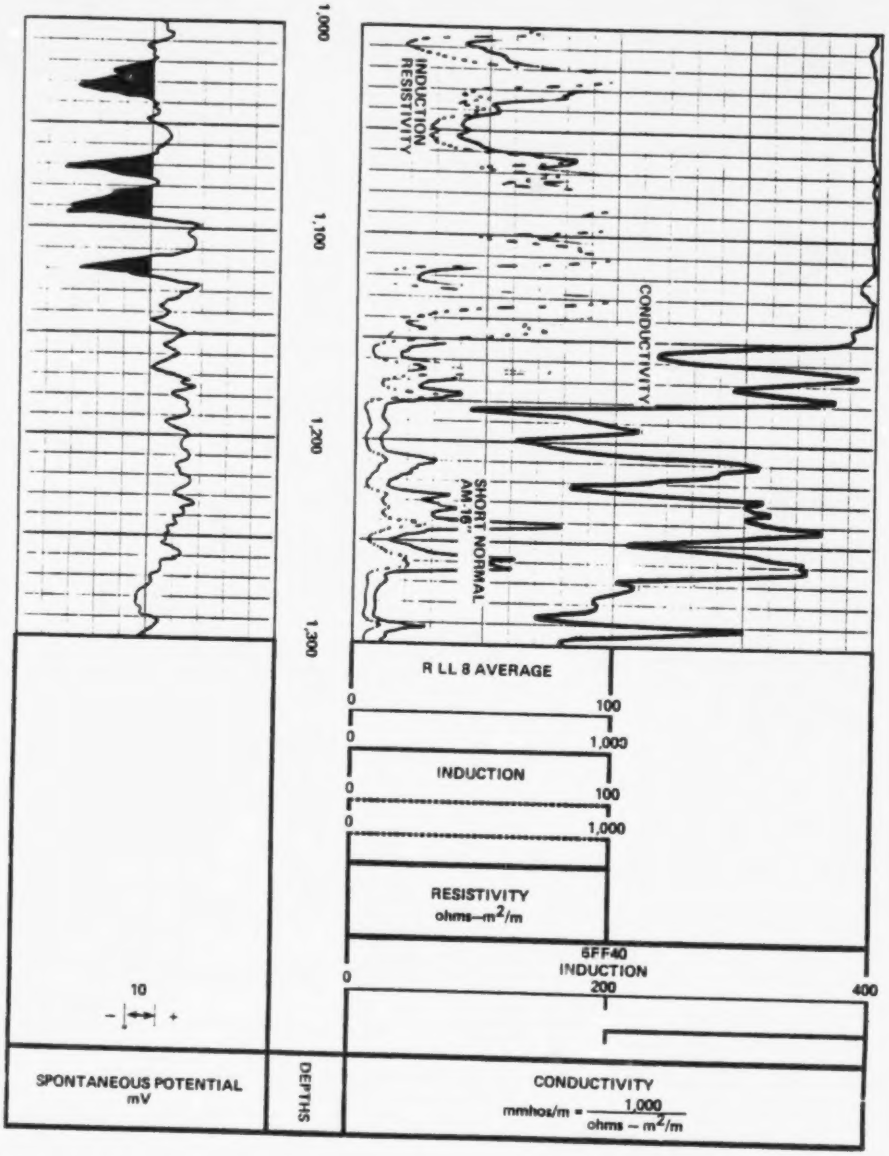


Figure 10. Correlation electric log for Tract C-a Well CE-705A.

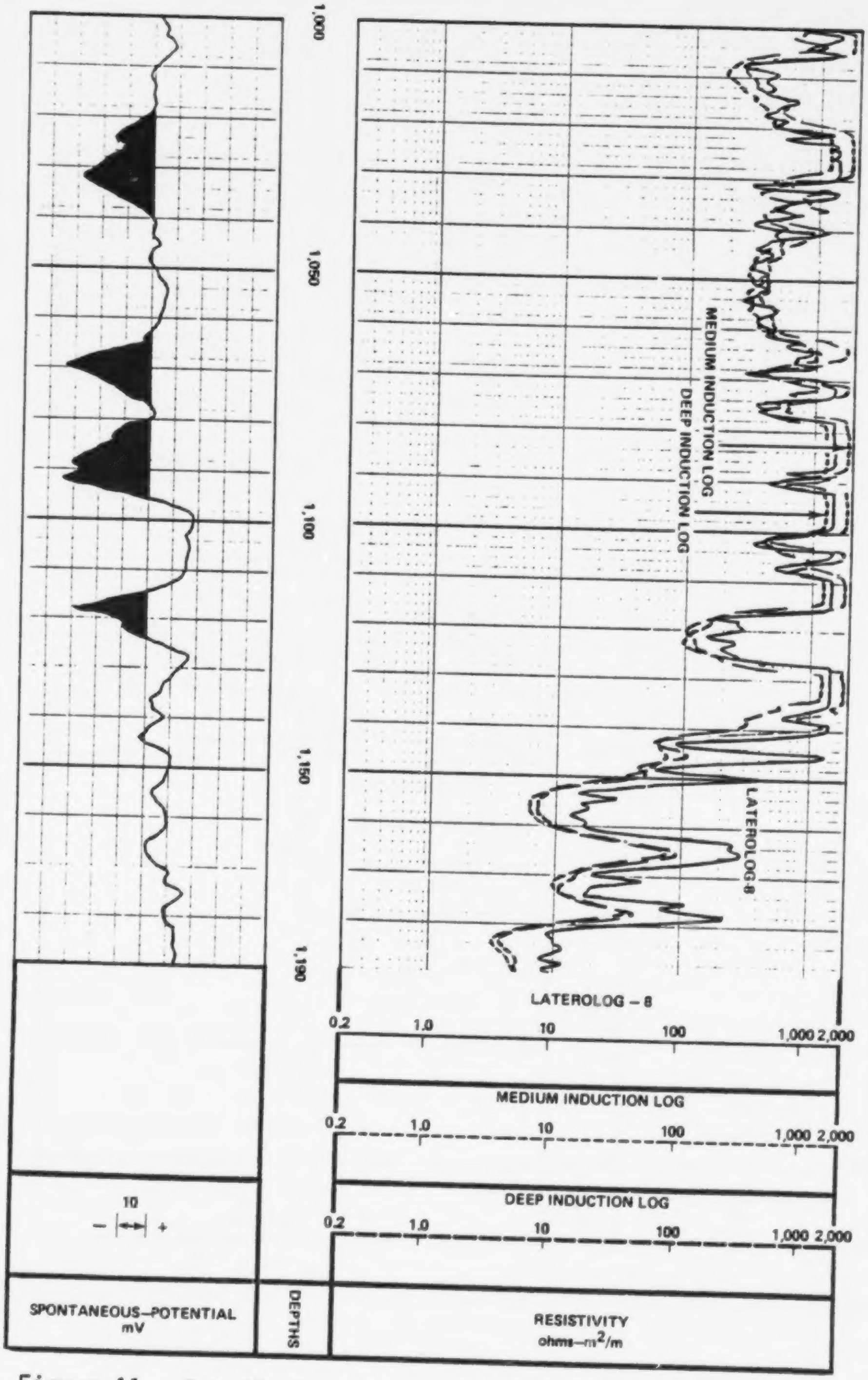


Figure 11. Detail electric log for Tract C-a Well CE-705A.

Spontaneous potential--The naturally occurring electric potential of a formation penetrated by a borehole is called the spontaneous potential, self-potential, or simply SP. It is generally printed on the left track of the log as shown in Figures 10 and 11. Two phenomena (electromechanical and electrokinetic) are thought to produce the potential current recorded in the SP log. The amplitude of the current is the cumulative effect of these phenomena taking place between the drilling fluid and the formation. For an SP current to be recorded, the well must be filled with a conductive fluid that can provide electrical continuity between the SP electrode and the formation. Furthermore, if this conductive fluid and the formation water have essentially equal resistivities the SP currents will be quite small and the log trace rather featureless. The existence of the SP current is also dependent on a certain minimum permeability that will allow ion migration between the drilling fluid and the formation.

The electromotive forces (EMF) of electrochemical origins are believed to be the largest contributor to the SP deflection. These are generated by differences in solution concentration between the drilling fluid and the formation water. For example, if the salinity of the drilling fluid is lower than that of the formation water, electric current flows into the formation opposite to the permeable zones, producing a negative (left) deflection on the SP log. Conversely, if the drilling fluid has a higher salinity than the formation water, a positive (right) deflection is recorded. Thus, the SP log is theoretically useful in the detection of permeable beds and in defining the location of their boundaries. This phenomenon may contribute to the shaded SP response shown in Figures 10 and 11. These negative deflections appear to define permeable beds in the Lower Aquifer system. The spinner log indicates significant fluid loss from the borehole that corresponds to the three upper deflections. However, no change in vertical flow velocity is found opposite the lowest stratigraphic SP deflection, nor do similar log anomalies up-hole indicate a change in water production on the spinner log. This may be caused by limitations inherent in the spinner log measurements or it may reflect relatively low permeability of the beds. Whether the beds are permeable or not, there is no direct relationship between the magnitude of the SP deflection and the permeability of the formation, nor is there any direct relation to porosity. Supplemental information from alternative geophysical logs is required for an accurate interpretation in this case.

The electrokinetic portion of the SP log is generated when the drilling fluid (an electrolyte) flows through a porous, nonmetallic medium (the mud cake) into the formation. The EMF is primarily produced opposite permeable formations where the pressure differential is maximum. Flow from the well bore into the formation produces a negative (left) SP deflection, and flow from a bed to the borehole produces a positive (right) deflection. The magnitude of the recorded potential is related to the velocity of the flow, resistivity of the electrolyte in the mud cake or formation, as well as several other factors. In general, the SP deflection generated by this electrofiltration is small and commonly considered negligible except for special situations that are comparatively rare.

Induction--The induction sonde consists of several receiver and transmitter coils. Constant intensity, high-frequency, electromagnetic waves are emitted from the transmitter coils, inducing secondary currents in the formation from the alternating magnetic fields set up by these waves. The eddy currents flowing through the formation produce their own magnetic fields that generate signals in the receiver coils. These induced signals are essentially proportional to the conductivity of the formation or inversely proportional to the resistivity. Variations of the transmitter/receiver coil spacing in the sonde produce deep- and medium-reading tools.

Focused-current resistivity--The focused current sonde consists of a central electrode symmetrically surrounded by additional pairs of interconnected electrodes. The potential difference of the surrounding (guard) electrodes is maintained at zero to focus the formation current into a thin sheet, which flows horizontally into the borehole wall. Focused-current devices provide better resolution than conventional resistivity tools in thin to moderately thick, highly resistive beds. Focusing sondes are available for use in deep, medium, and shallow depths of investigation.

The separation of deep and shallow resistivity measurements, whether induction- or focused-current-derived, is an indication of invaded or permeable zones. This separation occurs when the resistivity of the drilling fluid and the water in the invaded bed are sufficiently different to alter the resistivity of that bed near the borehole. Thus, if the resistivity of the drilling fluid is greater than that of the formation water, the shallow investigation tool should read higher than the deep-reading device.

In Figure 10, separation of the short-normal and induction-resistivity reading opposite the four negative SP deflections cannot be determined since both are off the linear scale. The logarithmic grid used in Figure 11 shows generally high resistivity values for the same section with no discernible separation between the deep- and shallow-reading tools. This suggests that invasion is so deep that it extends beyond the limits of the deep-reading tool. Water chemistry data indicate that a salinity difference exists between the borehole fluid and formation water, and the spinner survey shows a large quantity of water intake for this zone.

An order-of-magnitude change in the resistivity occurs below a depth of about 1,150 feet. Fischer analysis and lithologic records show no significant change in the oil shale stratigraphy at this depth, suggesting that the reduction in resistivity (increase in conductivity) can be related to more saline formation water below the Lower Aquifer system.

Cost Data--

Several combinations of resistivity log presentations are available from logging service companies. Two representative resistivity logs have been selected from each service company. The cost schedules for running these logs are given in Table 12.

Evaluation--

In general, shallow, fresh-water aquifer test holes in oil shale stratigraphy provide a poor working environment for electric logging devices. The

TABLE 12. COST SCHEDULE FOR VARIOUS RESISTIVITY LOGS (dollars)

Company/Service	Depth per foot	Depth minimum[a]	Operation per foot	Operation minimum[a]	Total minimum[a]
Birdwell[b]					
Induction electric	0.25	500.00	0.24	360.00	860.00
FS guard log	0.25	500.00	0.24	360.00	860.00
Schlumberger[c]					
Induction electrical	0.29	580.00	0.25	500.00	1,080.00
Dual-induction laterolog	0.30	600.00	0.25	500.00	1,100.00
Dresser Atlas[d]					
Induction electric	0.29	580.00	0.25	500.00	1,080.00
Dual-induction focused	0.30	600.00	0.25	500.00	1,100.00
Welex[e]					
Induction electric log	0.26	520.00	0.24	480.00	1,000.00
Dual-induction guard log	0.27	540.00	0.23	460.00	1,000.00

Notes:

[a] All service companies have a 2,000-foot minimum.

[b] Birdwell Rocky Mountain Price Schedule, June 1980.

[c] Schlumberger Rocky Mountain Price Schedule, October 1979.

[d] Dresser Atlas Rocky Mountain Price Schedule, July 1980.

[e] Welex Rocky Mountain Price Schedule, January 1980.

highly resistive (clear water) drilling fluids and oil shale rock mask or distort the normal SP and induction/focused current resistivity tool response, complicating the quantitative interpretation of these data. Specific conditions or observed log responses that hinder the utility of these data are given below:

- Spontaneous Potential
  - -- SP curves undergo gradual transition at bed boundaries in highly resistive oil shale environments. Therefore, permeable beds cannot be accurately located using the SP curve.
  - -- The highly resistive drilling fluids provide poor electrical continuity between the SP electrode and the formation.

  - Borehole fluids are used during drilling operations; therefore, the resistivity differences between formation waters and drilling fluids is small, reducing the character of the SP deflections.
  - Drilling muds are not always used during exploration studies; therefore, the pressure differential caused by the mud cake between permeable beds and the borehole may not develop, reducing the electrokinetic component of the SP curve.
  - Fluid motion common in Tract C-a wells tends to mask the true SP response.

- Induction/Focused Current Logs
  - Resistivity logs have not produced a clear separation between deep and shallow investigation tools for known permeable beds in the oil shale environment.
  - Conductivity measurements have a high degree of uncertainty in the nonconductive oil shale rock due primarily to instrument sensitivity at the low end of the scale.
  - Invasion of permeable zones will be extremely deep due to minimal mud cake development, masking true formation water resistivity determinations used in several alternative quantitative log interpretation techniques (not discussed here).

Bearing in mind the difficulties of using resistivity logging devices in oil shale environments, they are still useful in construction and the correlation of cross sections. However, information derived from log interpretation should be considered qualitative in nature.

Seisviewer Log

Principle of Operation--

The seisviewer sonde consists of a transmitter and receiver transducer mounted on a vertical axis that is rotated at a uniform rate during logging. In this configuration, the transmitting transducer emits a narrow-band acoustic signal to the entire inside diameter of the borehole as the instrument is lowered into the hole. The acoustic energy is transmitted through the drilling fluid, strikes the fluid formation boundary, and is reflected back to the receiving transducer. The amount of energy returned to the sonde is a function of the scatter caused by the physical properties of the borehole wall and attenuation in the borehole fluid. This signal is subsequently sent to the recording oscilloscopes at the surface via the wireline.

A flux-gate magnetometer is mounted on the vertical axis with the transducers and senses the earth's magnetic field. The sonde is then oriented by magnetic direction, as shown at the top right of Figure 12.

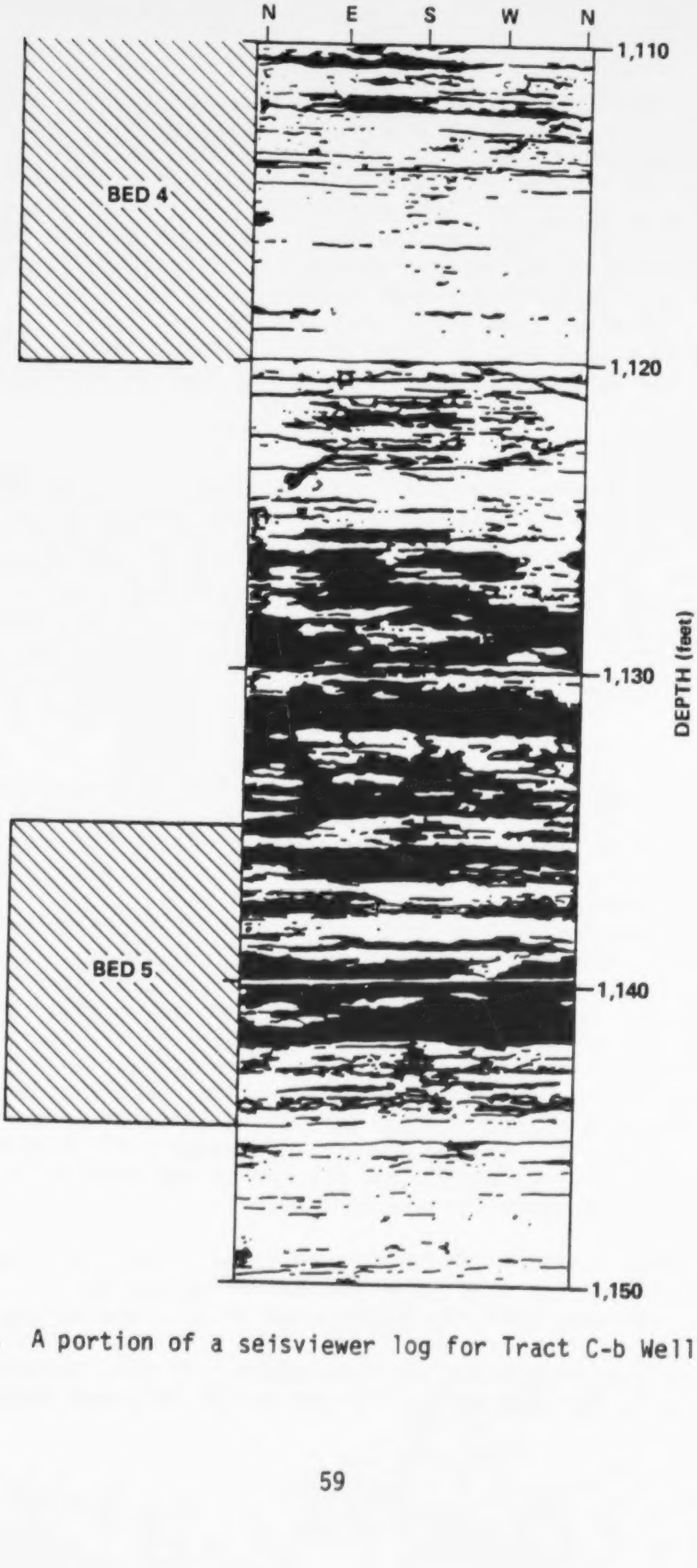


Figure 12. A portion of a seisviewer log for Tract C-b Well 32x-12.

The diameter of the sonde is 3-3/8 inches and can be operated in a 4- to 12-inch borehole. It is run in fluid-filled (water, mud, or oil base), cased or uncased holes.

The log presentation is an acoustic picture of the fluid formation boundary as if the borehole had been vertically dissected and layed out flat. The magnetic orientation of the log is given at the top of each log trace. Figure 12 shows a 40-foot section of a seisviewer log of Well 32x-12. Some of the features of the borehole wall depicted on the log are the sinusoidal curves at 1,122 and 1,125 feet. These are low angle fractures dipping to the north and south, respectively. Dark patches on the log are areas of weak signal return and represent vugs or beds that have eroded during drilling or completion operations. The sections from 1,115 to 1,120 feet and 1,145 to 1,150 feet are in-gage, competent rock with a strong signal return. Water production test zones 4 and 5 for Well 32x-12 are shown to the left of the log.

Cost Data--

Birdwell Division is the only logging company of those reviewed that has the facilities to operate a seisviewer. However, this logging tool has been pulled out of general use and can only be obtained by special request to the Birdwell office in Tulsa, Oklahoma. Although cost quotes were not developed for the seisviwer, it will be expensive to obtain this type of borehole imagery. A logging program involving several shallow oil shale exploration holes would be required to bring the unit cost per log into a comparable price range with other geophysical logging methods.

Evaluation--

Seisviewer logs are used to define vugs, fractures, breccia zones, washouts, and bedding planes in open holes. In the shallow, clear water, oil shale exploration holes, resolution of these physical features is excellent when the hole is close to the gage. These field data are extremely useful when production testing directly follows the logging operation. In this case, the seisviewer log can help guide the selection of hydrologic zones to be tested and aid in the placement of the testing equipment. In Figure 12, for example, water production for Bed 5 (between 1,135 and 1,145 feet) was recorded at 180 gpm, which was the third most productive zone tested in Well 32x-12. From the imagery in Figure 12 it appears that the upper test limit of Bed 5 does not conform to the upper part of the production zone. Based on the seisviewer log, the upper packer for a production test for Bed 5 should have been set in the more competent rock at a depth of 1,125 feet. This would have included the potentially permeable vugs and eroded bedding planes shown in the log, providing a more representative picture of the production to be expected from a mine shaft penetrating this horizon.

As indicated earlier, the seisviewer is no longer in widespread use. The electronic equipment for this labor-intensive logging method is costly to run and maintain. Viscous drilling fluids (mud or oil) and oblong or over-gage borehole diameters attenuate the signal, thus reducing resolution. The logging speed for high resolution is slow, about 5 ft/min, creating excessively long logging runs for deep wells. A combination of these factors has limited the usefulness of this logging method in the oil industry, thus reducing its overall utility and marketability. This is probably the primary reason why Birdwell has elected to provide the service on a limited basis.

HYDRAULIC TEST METHODS

Geophysical methods of determining hydrogeologic parameters in oil shale stratigraphy rely on direct or indirect measurements of the borehole wall, the surrounding rock, and the formation fluid to deduce the hydraulic parameters important to the development of an oil shale project. These methods, however, do not include a significant class of direct hydraulic testing procedures that provide detailed hydrology data through an evaluation of the response of the test well to the injection and removal of fluids. Hydraulic test methods are discussed in this subsection.

Well pump and injection tests range from simple, rather informal procedures conducted during a period of a few hours, to sophisticated hydraulic tests conducted over a continuous operational period of several weeks and involving numerous observation wells. To simplify the profusion of methods, testing procedures have been grouped into four general classes as follows:

1. Drill stem tests
2. Single packer tests
3. Dual packer tests
4. Long-term pump tests.

The groups are not intended to be inclusive, yet they provide a sufficiently large range of testing methods to meet the needs of most oil shale development projects. Each group is divided into three components including (1) test procedures, equipment, and costs, (2) analytical methods used to interpret test data, and (3) remarks. Actual test data from the Federal oil shale tracts are utilized wherever possible.

Review of the testing procedures, equipment, costs, and utility of the resulting data has led to the following priority ranking of the four general classes of tests:

- Dual packer tests provide horizon-specific hydrologic data at a minimal cost when multiple tests are conducted in a single borehole. Down-hole test equipment assembly allows for pumping, injection tests, and discrete water quality sampling.
- Long-term pump tests of aquifer systems produce the most representative regional data on boundary conditions and flow patterns. However, these tests are expensive and should be conducted by personnel knowledgeable in hydrologic principles.

- Single packer tests generate good-quality, bed-specific hydrologic information at about three to four times the cost of similar data gathered by dual packer tests (assuming a single-hole, multiple-test application). Field operation and procedures are simplified over the dual packer assembly.
- Drill stem test data is of limited value due to its nonspecific nature, high cost relative to the data return, and difficult interpretation. Drill stem tests are now seldom used in the development of oil shale tracts.

Drill Stem Tests

Test Procedures, Equipment, and Costs--

In conjunction with early exploration efforts, drill stem tests were routinely performed in core holes to define the hydrology of the Federal oil shale tracts. This kind of test includes the "informal pump tests" conducted on Tract C-a and the "jetting tests" performed on Tract C-b. Similar procedures were followed for both testing methods with some minor differences in the equipment utilized. Drill stem tests are performed in an open hole as follows:

- The borehole is drilled to the desired depth
- An air line is lowered down the drill stem to a point near the bottom of the string
- Air is blown or jetted through the air line, lifting the fluid in the drill string to the surface
- Discharge is measured as changes in water level through a Parshall flume or similar device and converted to a flow rate in gallons per minute
- Airlift pumping at a constant rate is maintained for a predetermined length of time (2 hours for Tracts C-a and C-b)
- Immediately following shutdown of the air compressor, a water-level measuring device is lowered down the drill string (depth sounder or water-pressure recorder)
- Recovery of the water level following shutdown is recorded
- If an observation tube is installed in the well, both drawdown and recovery-water-level measurements can be compiled.

On Tract C-a, drill stem tests were conducted after penetration of the B-groove and at the bottom of the borehole. This testing program was intended to provide hydrologic data on the Upper Aquifer system and on a combination of the Upper and Lower Aquifer systems. The majority of these tests are described in Rio Blanco Oil Shale Report (1974). On Tract C-b, from three to six drill stem tests were conducted on site wells and core holes. Test zones included top of Parachute Creek, top of mining zone, base of mining zone, and total depth of the hole. Raw data for these tests are given in C-b Shale Oil Venture, 1974.

Equipment required to perform a drill stem test, in addition to that commonly available on drill rigs, include an air compressor of sufficient capacity to overcome the pressure developed from the column of water within the drill string and a water-level measuring device. A geologist or hydrologist should be present to supervise the test.

Costs for each test are based on the total rig time, equipment cost or rental, labor for supervision, and the number of tests conducted. Individual tests should run from $600 to $750 for the short (4- to 5-hour) tests. Longer tests are more expensive, depending on the amount of additional labor and rig time involved.

Analytical Techniques--

The time-recovery data compiled during the drill stem tests are used to calculate transmissivity (T) and specific capacity. T is the rate at which water will flow through a unit width of aquifer fully penetrating the saturated thickness under a unit hydraulic gradient. T has dimensions of length squared per unit of time because it represents flow through a vertical strip of unit width. Specific capacity is yield per unit drawdown expressed in gallons per minute per foot or gallons per day per foot.

Analytical methods for determining these parameters are derived from Theis' nonequilibrium formula (Theis, 1935). A straight-line, or graphical, solution for a modified Theis equation was discussed by Cooper and Jacob (1946) and has been used by both tract developers to calculate T. A concise description of this graphical solution is presented in Miller (1973). The general method is as follows:

- Time-recovery data are plotted on semilog paper, recovery (in feet) on the arithmetic scale and time (in minutes) on the log scale
- The slope (Δ_s) is determined by the change in water level (recovery) through one log cycle of time
- Transmissivty (T) is then calculated from the following formula:

$$T = \frac{(264)(Q)}{\Delta_s} ,$$

where: Q is the constant recovery (drawdown) discharge (gpm)

Δ_s is the slope (feet)

T is the transmissivity (gpd/ft).

The success of the straight-line solution is based on the assumption that the recovery time is long and the radius of the observation point to the pumping (recovering) well is small such that the straight-line approximation coincides with the Theis-type curve. This constraint is met within the first few minutes of recovery (pumping) when measurements of the water level are taken in the pumping well.

Relatively few, if any, of the aquifers in fractured oil shale stratigraphy will conform to the basic hydrologic assumption of infinite extent in all directions from the pumping well used by Theis to develop the flow equations. Geologic and hydrologic boundaries affect the slope of the time-recovery (drawdown) plot. Impervious boundaries limit the flow of water to the pumping well, causing a more rapid deepening on the cone of depression and steepening the slope of the time-drawdown curve. Conversely, impervious boundaries increase the rate of recovery and steepen the slope of the time-recovery curve when calculated recovery (drawdown extended through the recovery period minus residual drawdown) is plotted against time. Recharge boundaries have the reverse effect on the slope in the straight-line solution. Recharge water entering the well flattens the slope of the curve. Qualitative evaluation of boundary conditions from the graphical solution are useful in defining the hydrogeologic framework of the study area and in planning more detailed hydraulic testing programs. A more detailed discussion of boundary conditions on well hydraulics is given in Chapter 6 of Johnson (1975).

More sophisticated approaches are available to define T from confined-aquifer, unsteady-state drawdown/recovery data. These include Theis' straight-line recovery method (Theis, 1935), Theis' curve-fitting method (Jacob, 1940), and Chow's nomogram method (Chow, 1952). However, the additional time required to interpret the data from these methods is difficult to justify in that the data sets are from thick, complex aquifer sequences that are not adequately represented by the simplified models used to develop the interpretational theory.

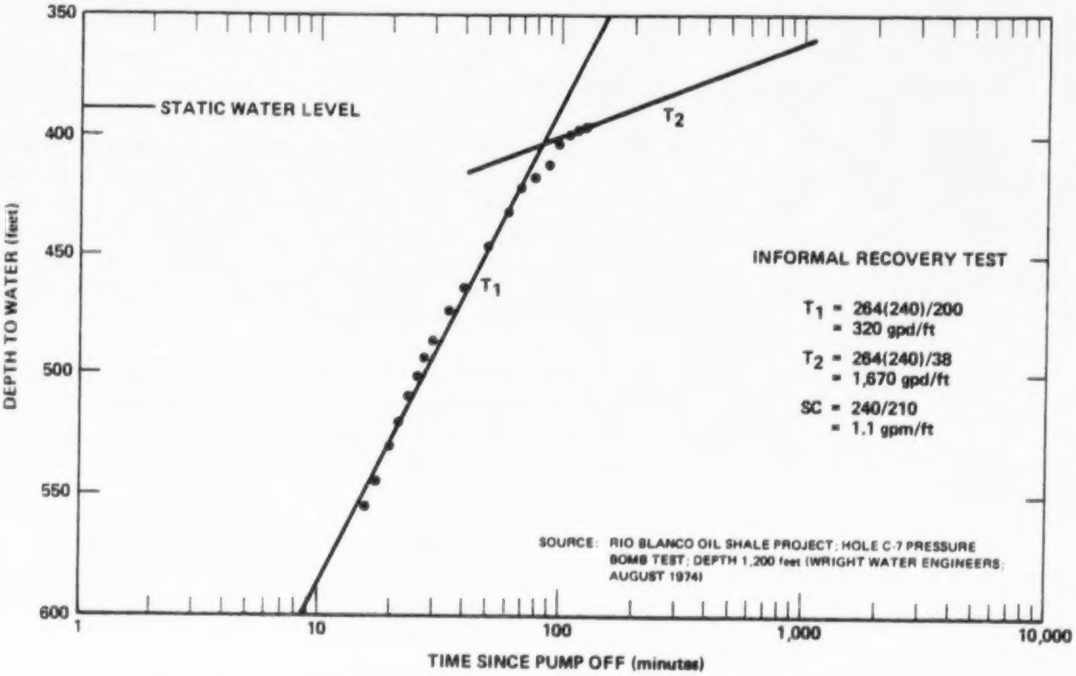
Remarks--

Review of the drill stem test data submitted to the Area Oil Shale Supervisor indicated that the "informal pump tests" provided ranges for T based on the straight-line solution to the time-recovery data. Noting a change in slope of the plot and the implicated boundary condition, T values were calculated using Jacob's method with Δ_s values derived from the primary and secondary slopes of the graph (Figure 13). This is not consistent with standard methods derived from the Theis nonequilibrium formula. The following is stated in Johnson (1975), p. 118, regarding such an interpretation:

> It should be pointed out in passing that calculation of the transmissibility, T, of the water-bearing formation must be made from the value of Δ_s corresponding to the slope of the first part of the time-drawdown (recovery) graph. Beyond the point where a change in slope occurs, a numerical value that may represent the slope of the second part of the graph is of no significance in analyzing the pumping (recovery) test data. No attempt should be

> made to use any such value in either the Theis non-equilibrium or modified non-equilibrium formulas.

Therefore, T values calculated in this manner have no theoretical basis and can be extremely misleading to tract developers.



SOURCE: RIO BLANCO OIL SHALE PROJECT; HOLE C-7 PRESSURE BOMB TEST; DEPTH 1,200 feet (WRIGHT WATER ENGINEERS; AUGUST 1974)

Figure 13. Jacob's straight-line solution for T.

Well completion reports (drill stem tests) for eight core holes on Tract C-a show that boundary conditions usually affected the time-recovery plots within the first 20 to 30 minutes of recovery. Without exception, impermeable boundary conditions were indicated by these time-recovery curves. This is to be anticipated in an aquifer where permeability is fracture-controlled because of the low permeability of the unfractured matrix rocks. The tests should have been conducted for a long enough period of time to observe if recharge water had broken into the well in response to the head difference in the fracture system created by pumping; thus the true nature of the boundary could have been determined.

Raw data for 55 drill stem tests are given in Table 11 B-4, C-b Shale Oil Venture (1974). These data have not been plotted to check the analytical procedures used to calculate T values.

A serious disadvantage of the drill stem test, and rendering less value to the calculated parameters, is that T is obtained for the entire open portion of the borehole and no zone-specific information is obtained. In addition, when combined (Upper and Lower Aquifer systems with differing pressure heads that create production and "thief" zones) drill stem tests are conducted, it is unlikely that the straight-line solution will adequately model the well conditions from which T values are to be calculated. For these and other reasons, drill stem tests on both Tracts C-a and C-b were discontinued early in the exploration/data-gathering phase of development.

Single Packer Tests

Test Procedures, Equipment, and Costs--

Testing methods included here are single packer drawdown/recovery and injection-pressure permeability tests. Test procedures for the former are similar to those discussed for drill stem tests except that a packer is lowered on drill pipe to a point above the bottom of the hole (approximately 50 feet on Tract C-b), water is lifted or jetted from the packed-off section, and water-level measurements are compiled. The packer is then removed, the hole deepened to the next zone of interest, and the test repeated.

Equipment for the packer test includes an air compressor, a string of drill pipe, and a packer. Inflatable packers, as opposed to compression or leather cups, are recommended because they seal better on rough walls or in irregular shaped holes, reduce testing time, and are therefore more economical.

Costs for running a single packer drawdown/recovery test requires rig time to set the packer in addition to labor and equipment for a standard drill stem test. The cost (in 1980 dollars) is estimated to be $1,800 to $2,000 per test.

The injection-permeability test is run by drilling the borehole to the desired depth, pulling the drill string, and seating the packer at the desired depth above the bottom of the hole. The section is flushed out to remove drilling fluid and water is pumped under pressure into the test zone. The constant pump discharge (Q) and applied pressure (H_2) are recorded. Following completion of the test, the hole is deepened to the next test horizon and the procedure repeated.

Pressure-permeability tests on Tract C-b were run in conjunction with drawdown/recovery tests. The procedure varies slightly from the injection test in that after the packer is set, a valve is opened to allow formation fluid to flow into the drill pipe, thus reducing the hydrostatic pressure in the test section. The valve is then closed and data on the pressure recovery are recorded. A pump test is performed following recovery of the hydrostatic pressure. The injection pressure test is then conducted by pumping water at a constant rate into the test section and observing the pressure change in the drill pipe. Commonly, several different injection rates are used during the test.

Single packer injection-permeability tests require substantially more equipment than pump tests, including a centrifugal test pump, a water meter to measure injection flow rates, connection pipes, a swivel plug valve, a pressure gage and sub for the gage, etc. Further details on equipment requirements and arrangement for testing are given in Bureau of Reclamation (1977). In addition to the above equipment, a clear source of water is required for testing. This can be discharge from local wells or springs but should be of equal or better quality (lower TDS) than the formation fluid in the test zone. In arid areas this water may have to be trucked to the test site and can become a substantial cost item.

The injection pump is the primary piece of test equipment. Tests are usually run using the rig's mud pump. These multiple-cylinder-type pumps usually have a maximum capacity of from 25 to 30 gpm and provide acceptable test results only when low permeabilities or short test sections allow development of back pressure on the formation. In addition, since the fluctuating pressure through this type of pump is difficult to read accurately, it is recommended that a suitable centrifugal pump be obtained for testing.

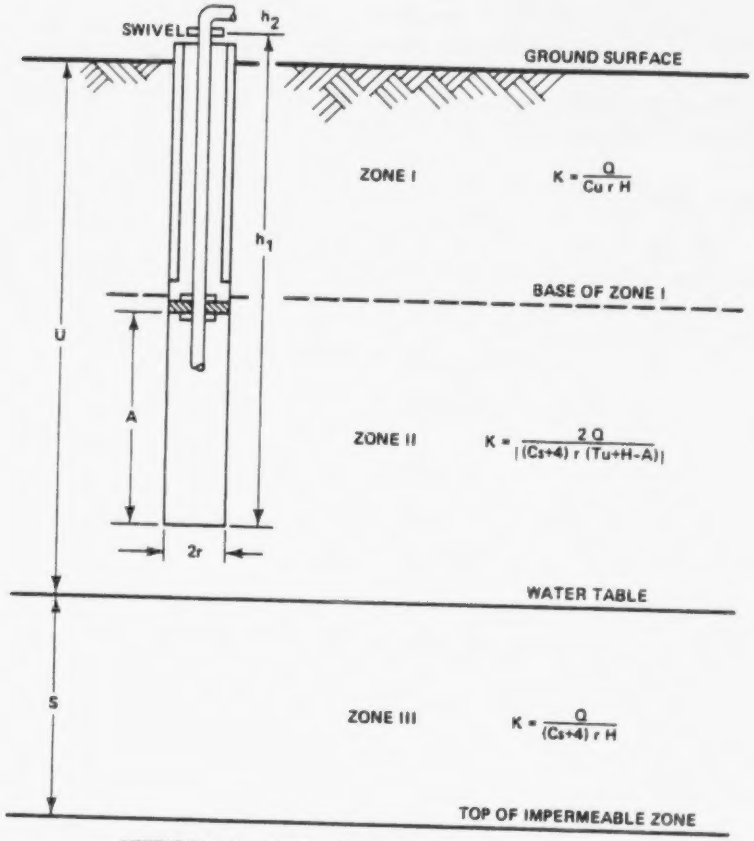
Tests should be run for 20 minutes or longer with readings of injection rates (gpm) and applied pressure (psi) taken at 5-minute intervals. Pressure can be increased during the test to determine rock characteristics but, to prevent blowouts or fracturing the borehole wall, it should not be taken too high. As a general rule-of-thumb, safe pressure in consolidated rock is 0.5 psi per foot of depth from the ground surface to the upper packer.

Costs for the injection test vary with the availability of a suitable injection fluid and the cost of obtaining the surface equipment. It is estimated (in 1980 dollars) that $2,200 to $2,600 per test would cover the equipment, operation, and labor costs incurred by a single packer injection permeability test.

Analytical Techniques--

T values can be calculated from a single packer drawdown/recovery test using methods discussed under "Drill Stem Tests" in this section. Injection-permeability tests are discussed in Ahrens and Barlow (1951). Figure 14 is a reproduction from this report that shows the setup for the single packer permeability test. Parameters measured during testing are as follows:

1. Elevation of the ground surface at the test site (feet)
2. Radius of the hole, R (feet)
3. Length of the test section (the distance between the packer and the bottom of the hole), A (feet)
4. Depth from ground surface to bottom of the hole (feet)
5. Distance of swivel above ground surface (feet)
6. Applied pressure of head, H_2 (psi or feet)
7. Steady flow into well at 5-minute intervals, Q (gpm)


SWIVEL
h_2
GROUND SURFACE
ZONE I
$K = \frac{Q}{Cu\, r\, H}$
h_1
BASE OF ZONE I
U
A
ZONE II
$K = \frac{2Q}{[(Cs+4)\, r\, (Tu+H-A)]}$
2r
WATER TABLE
S
ZONE III
$K = \frac{Q}{(Cs+4)\, r\, H}$
TOP OF IMPERMEABLE ZONE

LIMITATIONS: $Q/a < 0.10$, $S > 5A$, $A > 10r$

K = Coefficient of permeability (ft/sec) under unit gradient
Q = Steady flow into well (cfs)
H = Effective head = $h_1 + h_2 - L$ (ft)
h_1 = In test above water table, distance between swivel and bottom of hole in tests below water table (ft); distance between swivel and water table (ft)
h_2 = Applied pressure at collar (ft); 1 psi = 2.31 feet
L = Head loss in pipe due to friction; for quantities less than 4 gpm in 1¼" pipe, it may be ignored (ft)
X = Percent of unsaturated strata ($X = H/Tu$)
A = Length of test section (ft)
r = Radius of test hole (ft)
Cu = Conductivity coefficient, unsaturated bed
Cs = Conductivity coefficient, saturated bed
U = Thickness of unsaturated material (ft)
S = Thickness of saturated material (ft)
Tu = $U - D + H$
D = Distance from ground surface to bottom of hole (ft)
a = Surface area of test section (ft); in Method I area of wall plus area of bottom; in Method II area of wall

Figure 14. Single packer injection test setup (after Ahrens and Barlow, 1951).

8. Nominal size of pipe (inches) and length of pipe (feet) between swivel and packer

9. Thickness of saturated material above a relatively impermeable bed, S (feet).

In addition to the these measurements, head loss in the drill pipe due to friction (L), saturated bed conductivity coefficients (Cs), and a definition of boundary conditions between Zones 1 and 2 are required to interpret test results. Graphs required to determine these parameters and numerical examples are provided in Ahrens and Barlow (1951).

Multiple pressure injection tests are performed in the same manner as described above except that the pressure is applied in more than one essentially equal steps. The applied pressure can be estimated by determining the maximum safe pressure and dividing by the number of pressure steps desired.

Synthetic test results of multiple pressure tests for varying formation conditions have been postulated in Bureau of Reclamation (1977). These are given in Figure 15. Circled numbers on Figure 15 denote the following probable conditions:

1. Probably very narrow, clean fractures; laminar flow; low permeability with discharge directly proportional to head

2. Firm, practically impermeable material; tight fractures; little or no intake regardless of pressure

3. Highly permeable, relatively large open fractures indicated by high rates of water intake and no back pressure (pressure shown on gage due entirely to pipe resistance)

4. High permeability with open and permeable fractures containing filling material that tends to collect in traps and retard flow; turbulent flow

5. High permeability; contains fracture filling material that washes out and increases permeability with time; fractures probably are relatively large; turbulent flow

6. Similar to (4) but tighter fractures and laminar flow

7. Packer failed or fractures are large and have been washed clean -- highly permeable; turbulent flow (test takes capacity of the pump with little or no back pressure)

8. Fairly wide and open fractures filled with clay gouge material that tends to pack and seal under water pressure (takes full pressure with no water intake near end of test)

9. Open fractures with filling that tends to block and then break under increased pressure; probably permeable; turbulent flow.

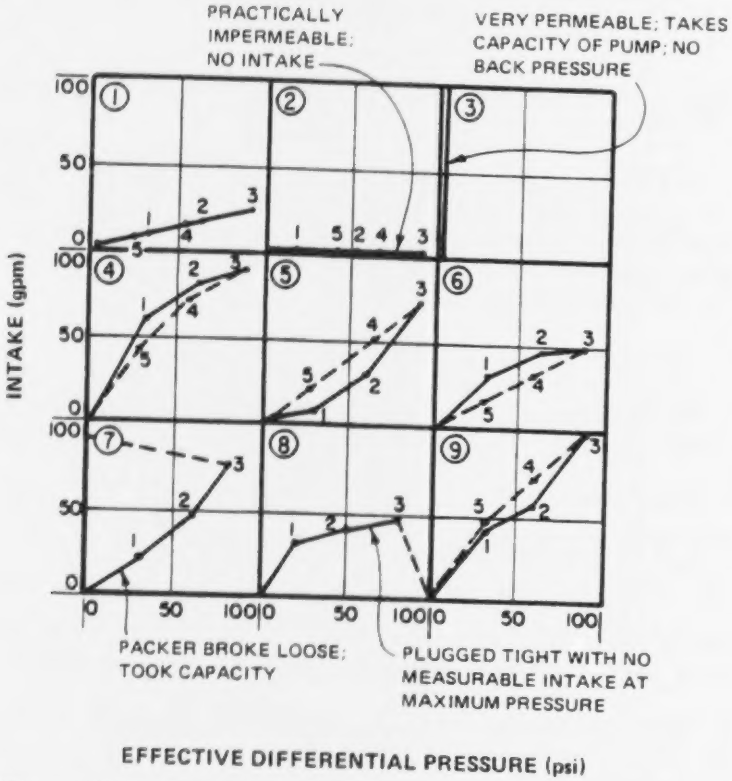


Figure 15. Plots of simulated, multiple pressure, permeability tests (after Bureau of Reclamation, 1977).

Tract C-b developers used a technique presented by Horner (1951) to analyze the pressure-recovery data from the single packer tests. This method is essentially the same as Jacob's straight-line solution except that pressure in psi is plotted against time on semilog paper instead of water levels in feet.

A drawdown analysis presented by Odeh and Jones (1965) on Tract C-b was used to analyze the multiple-pressure, single packer injection tests. Although developed primarily for formation evaluation from oil and gas wells flowing at variable rates, this technique has had wider application. Analysis of field data is conducted as follows (for greater detail, see Odeh and Jones, 1965):

- Production in barrels per day is plotted on regular graph paper versus time in appropriate units (minutes)
- Average flow rates for specific time increments are calculated

- The change in pressure, Δp, (original formation pressure minus flowing bottom-hole pressure) is determined and divided by the average flow rate (q_n) for each increment, $\Delta p/q_n$
- The summation of the different flow rates divided by the last flow rate is calculated as a function of time from the following expression and plotted against $\Delta p/q_n$

$$\frac{1}{q_n}\sum_{i=0}^{n-1} \Delta q_i \log(t_n - t_i) \quad ,$$

where: q_n is the last flow interval (bpd)

q_i is the i^{th} flow interval (bpd)

t_n is the total flow time (minutes)

t_i is the flow time for each change in rate (minutes)

- The slope (m) of the resulting straight-line plot is determined
- T is calculated from the formula $T = 7.06\ \mu/m$ (where μ is the viscosity of the fluid in centipoise).

T values and permeability for single packer tests in Well SG-17 were calculated as described above. Computer plots from the analysis are given in the C-b Shale Oil Venture (1979).

Remarks--

Single packer tests have performed well in the oil shale stratigraphy on the Federal tracts. Analytical methods for data interpertation are readily available.

Detailed information was compiled for Tract C-b, borehole SG-17, where 40 single packer tests were performed. These data provided a composite picture of horizontal transmissivity through the lithologic section penetrated by the well. These data were the primary input parameters for a computer model specifically designed for the Tract C-b mining and reinjection program. As such, the accuracy of these parameters is extremely important to the oil shale project. These computer-derived permeabilities are not consistent with values for the same test sections presented to the area oil shale office in February of 1975 (C-b Shale Oil Venture, 1975). In addition, test results would be more easily evaluated if they were presented in generally accepted water supply units (gpd/ft^2) rather than Darcy units adopted in petroleum engineering.

The primary drawback in using the single packer test method is that it is very costly. Setting up the pump for injection and the "round trip" for the rig to set and remove the packer is time-intensive. Because the tests are run prior to completing the well or core hole, geophysical logs useful in directing the hydrologic program by defining test beds cannot be utilized. These drawbacks are in part overcome through hydraulic testing using the dual packer method described below.

Dual Packer Tests

Procedures, Equipment, and Costs--

Dual packer tests have been run on Tract C-b and are referred to as "mini-pump tests" in the C-b Shale Oil Venture (1979).

In general, the test procedure is to drill the borehole to its final depth. The drill string is then removed and geophysical logs can be run in the open hole at this point if they are part of the overall testing program. The dual packer assembly is lowered to the bottom of the borehole and testing proceeds upward through the zones of interest. The packer assembly is set straddling the test zone and the desired test(s) are run. The packers are then deflated and moved up the hole to the next test horizon.

The equipment utilized in dual packer testing includes the packers, a submersible pump, a multipurpose valve, and pressure transducers. The straddle packers should be gas-inflatable so they can be deflated and reinflated without requiring a return to the surface for redressing. This allows testing of all zones during one trip into and out of the hole. A submersible pump should be installed between the packers so that water samples and pump test data can be collected. The multiple-purpose valve installed between the packers and above the pump provides access to the packed-off zone for fluid injection and can be sealed off during pump testing. Pressure transducers installed above, below, and in the packed-off zone are used to measure pressure changes and detect packer failure. Surface equipment is be similar to that described for the single packer test.

In 1978, the U.S. Geological Survey (USGS) developed a custom packer assembly for hydrologic testing and hydrofracturing by modifying a production injection packer manufactured by Lynes, Inc., of Houston, Texas. This equipment was tested in the Piceance Basin. Study results are documented in U.S. Geological Survey (1978).

The USGS tests show that the dual packer assembly requires from one-quarter to one-third less time than a standard single packer assembly for the same hydrologic test because several tests can be performed on one round trip. Costs are cut in nearly direct proportion to the time saved, resulting in costs of about $500 for a 4- to 5-hour pump test and about $650 for an injection test (if water is trucked to the test site).

Analytical Techniques--

Dual packer tests on Tract C-b were conducted in 1975 in twin holes SG-1 and SG-1A. Equivalent test zones with rich oil shale beds were isolated in each well with straddle packers and pump and injection tests performed. Semi-confined, unsteady-state conditions described by Hantush and Jacob (1955) were used to model the aquifer. Solutions for the unsteady-state flow have been described by Walton (1962) and Hantush (1956). These analytical methods are discussed below.

Walton's method is a curve-fitting procedure from which transmissivity, storage coefficient, hydraulic resistance of a semipervious layer, and leakage factor of the water-bearing stratum can be determined. The reasoning used to develop the solution is similar to Theis' method except there are several type curves instead of one. This family of curves can be drawn from data published by Hantush (1956) or found in Walton (1962).

The analytical procedure of Walton is as follows:

- A family of type curves is developed on double-logarithmic paper
- Drawdown versus time is plotted on double-log paper of the same scale as that used for the family of curves
- Observed data is superimposed over the family of type curves and the best fit is found keeping the x- and y-axes parallel
- A match point on the superimposed observed data sheet is selected and the four corresponding parameters are read
- These values are substituted into the appropriate equations and the hydrologic parameters of interest calculated.

Hantush's Method I (Hantush, 1956) solution uses the inflection point of the time-drawdown data plotted on semilogarithmic paper. To determine the inflection point, the steady-state drawdown (maximum drawdown) is required and should be known through direct observation or by extrapolation. This method uses data from a single observation piezometer. The solution is developed as follows:

- A plot on semilogarithmic paper of drawdown versus time (time on the logarithmic scale) is prepared and the best fit curve is drawn through the plotted points
- Determine the value of the maximum drawdown by extrapolating the plotted points through time
- Calculate the inflection point (Sp) on the curve using the formula (see Hantush, 1956),

$$Sp = \frac{Q}{4\pi kD} Ko(r/L) \quad ,$$

where Q is the discharge

k is the hydraulic conductivity

D is the saturated thickness

r is the distance from the pumping well to the observation well

L is the leakage factor of the water-bearing layer

Ko is the Bessel function

- Read the value of time (tp) that corresponds to Sp
- Determine the slope of the best fit curve at the inflection point (ΔSp) by the change in slope over one log cycle that includes the inflection point, or by the tangent to the curve at the inflection point.
- Substitute the values at Sp and ΔSp in the formula,

$$\frac{2.30\ Sp}{\Delta Sp} = e^{r/L}\, Ko(r/L) \quad ,$$

and determine the value of r/L by extrapolation from tables in Hantush (1956)

- Transmissivity (kD) is then calculated using the equation,

$$\Delta Sp = \frac{2.30\ (Q)}{4\pi kD}\, e^{r/L},$$

and a table of values for e^{-x} (Hantush, 1956)

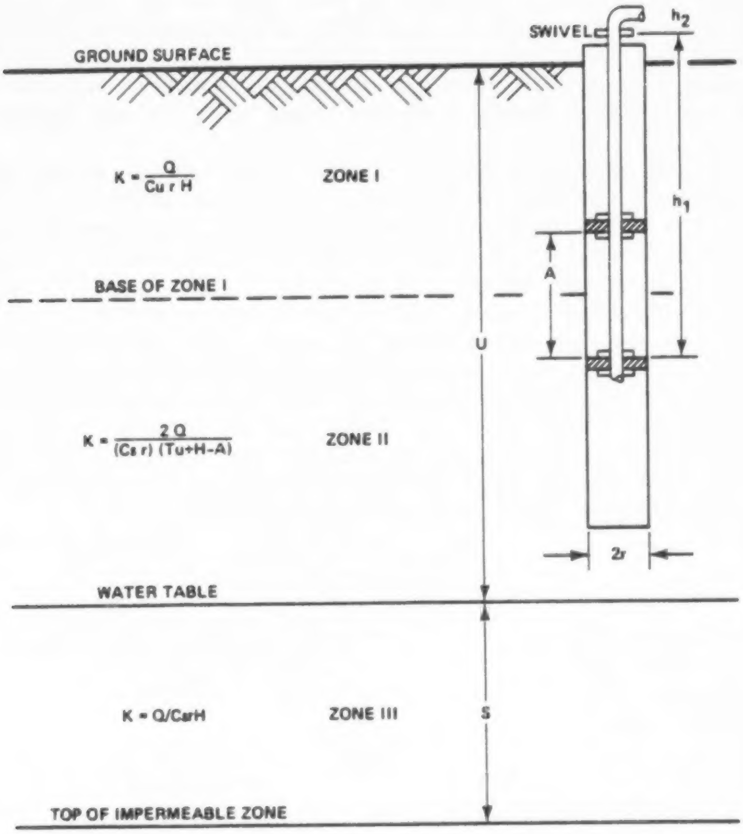
- The storage coefficient (S) can then be calculated using the following equation:

$$S = \frac{4kD(tp)}{2rL}$$

- Hydraulic resistance (c) of the semipervious layer is then found from the relation, $c = L^2/kD$.

Injection permeability tests can be analyzed using the method of Odeh and Jones (1965) described earlier. An alternative injection test is presented in Ahrens and Barlow (1951) for steady flow conditions. Figure 16 is a diagram of the test setup and equations used to calculate the permeability coefficient (K). Measurements taken during testing are the same as those for a single packer test (see page 67) with the following exceptions:

3. Length of test section, A, is the distance between the packers (feet)
4. Depth, D, is measured from the ground surface to the uppermost part of the lower packer.


SWIVEL
h_2
GROUND SURFACE
$K = \frac{Q}{Cu\, r\, H}$
ZONE I
h_1
A
BASE OF ZONE I
U
$K = \frac{2Q}{(Cs\, r)(Tu + H - A)}$
ZONE II
2r
WATER TABLE
K = Q/CsrH
ZONE III
S
TOP OF IMPERMEABLE ZONE

LIMITATIONS: $Q/s \leq 0.10$, $S \geq 5A$, $A \geq 10\,r$; in Method II, thickness of each packer must be $\geq 10\,r$.

K = Coefficient of permeability (ft/sec) under unit gradient

Q = Steady flow into well (cfs)

H = Effective head = $h_1 + h_2 - L$ (ft)

h_1 = In test above water table, distance between swivel and bottom of hole in tests below water table (ft); distance between swivel and water table (ft)

h_2 = Applied pressure at collar (ft); 1 psi = 2.31 feet

L = Head loss in pipe due to friction; for quantities less than 4 gpm in 1¼" pipe, it may be ignored (ft)

X = Percent of unsaturated strata (X = H/Tu)

A = Length of test section (ft)

r = Radius of test hole (ft)

Cu = Conductivity coefficient, unsaturated bed

Cs = Conductivity coefficient, saturated bed

U = Thickness of unsaturated material (ft)

S = Thickness of saturated material (ft)

Tu = U − D + H

D = Distance from ground surface to bottom of hole (ft)

s = Surface area of test section (ft); in Method I area of wall plus area of bottom; in Method II area of wall

Figure 16. Dual packer steady flow injection test (after Bureau of Reclamation, 1951).

Remarks--

Dual packer tests were conducted in only two holes, SG-1 and SG-1A on Tract C-b. In each of these holes a single, interconnected horizon was isolated and tests run without moving the packers. This testing method did not utilize the primary economic advantage of the dual packer assembly, namely, the ability to run several tests from one round trip in the borehole.

Analysis of the pump test data from the same section using Walton's method shows large variations in T values. This variation could be caused by inaccuracies in the water level, pressure measures (pressure measurements are only accurate to ±1/4 foot), or significant leakage through the semipervious layer during testing, which makes a unique fit to the family of curves difficult. T values calculated by the Walton and Hantush methods show relatively close agreement but are low in relation to other test results for the same bed. The accuracy of Hantush's method depends on precision water-level measurements and the estimation of the steady-state (maximum) drawdown. Fortunately, an independent check of T, S, and L can be made by substituting these parameters into equations presented by Hantush and Jacob (1955) and calculating drawdown and time values that should fall within the observed data points. The equations utilized in this check are as follows:

$$s = \frac{Q}{4\pi kD} W(u,r/L)$$

and

$$u = \frac{r^2 S}{4kDt}$$

where s = drawdown in the observation piezometer a distance r from the pumping well

kD = aquifer transmissivity

S = coefficient of storage

t = time since pumping started

and w(u,r/L) is the "well function" for a specific piezometer with distance r from sampling well and leakage factor L.

Long-Term Pump Tests

Procedures, Equipment, and Costs--

Long-term pump tests have been conducted on both Tracts C-a and C-b. Procedures for performing this type of test are given in numerous hydrology texts. Chapter 10, Bureau of Reclamation 1977 Ground Water Manual provides an in-depth discussion of acceptable methods, instrumentation, and required equipment for pump testing.

Cost items are similar to those for a dual packer pump test (with or without the packers) and include labor, operation, and equipment. Total costs can range from $3,000 up to $10,000 for a more sophisticated long-term test with multiple observation wells.

Analytical Techniques--

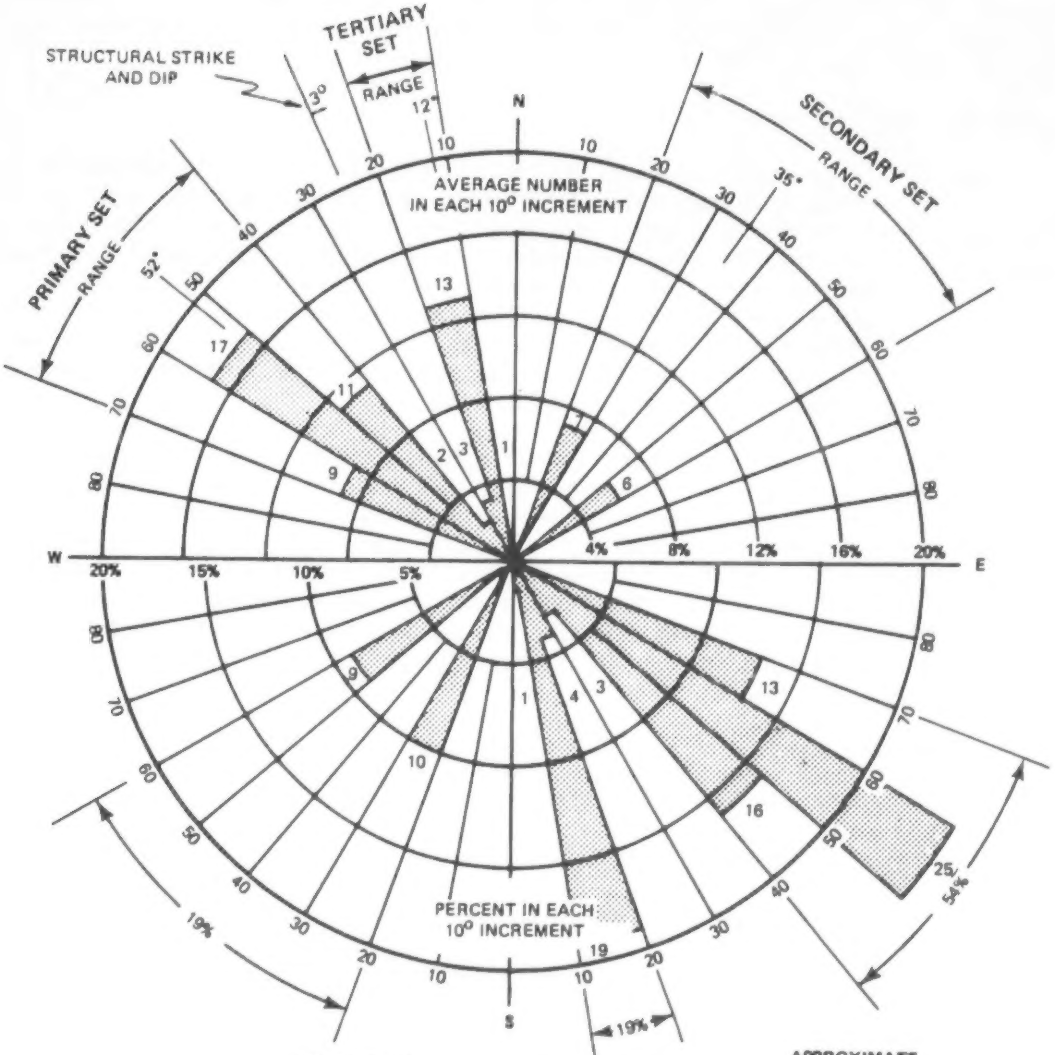
Long-term pump tests provide the most representative information on aquifer characteristics and boundary conditions. Analytical methods used by tract developers are similar to those discussed earlier and include curve fitting, calculation, and straight-line solutions. These methods have been developed for isotropic aquifers and therefore provide average values of the hydraulic parameters in anisotropic systems. Little information is developed for the maximum and minimum flow directions or rates that are important in mine design and developing dewatering programs. Anisotropic aquifer solutions that address these shortcomings are discussed below.

Fracture-controlled aquifers in oil shale stratigraphy are prone to exhibit anisotropic flow with the principal axis parallel to the strike of the primary fracture system. The shape of the drawdown cone for the Upper Aquifer on Tract C-a, as defined by Weeks et al. (1974), is elliptical, indicating a strongly anisotropic aquifer. Several solutions to unsteady-state flow in confined or unconfined anisotropic aquifers have been presented by Hantush (1966) and Hantush and Thomas (1966). Alternate analytical methods are used based on available information for the anisotropic system. This information can be grouped into three cases:

- Principal direction of anisotropy known
- Principal direction of anistropy not known
- Drawdown ellipse for test well known.

Solutions for these cases will be discussed in turn.

Principle direction of anisotropy known (Hantush method)--Geological and geophysical surveys of Oil Shale Tract C-a evaluated surface fault and joint systems. These data have been condensed into rose diagrams showing principal and subset joint and fracture systems. Figure 17 shows surface joint strikes from the outcrops in the vicinity of the mine development plan (MDP) area, Tract C-a. The primary joint set ranges from N40-70°W with N52°W as the average strike direction. Secondary and tertiary joint sets are also shown in the diagram and both have a joint frequency of two to five relative to the primary system. Figure 18 shows a rose diagram of photolinear strikes within the MDP area, Tract C-a, from work conducted by R.A. Hodgson (1979). The primary linear sets ranges from N45-75°W with N61°W as the average strike direction. Alternate joint systems are also presented in Figure 18. These data are in agreement with the surface geologic study and suggest the principal anisotropic flow axis should be about N57°W. Assuming that these data accurately define the principal direction of anisotropic flow (field data show principal flow direction more to the east), and that information from at least two groups of observation wells on different radial lines from the pumped well

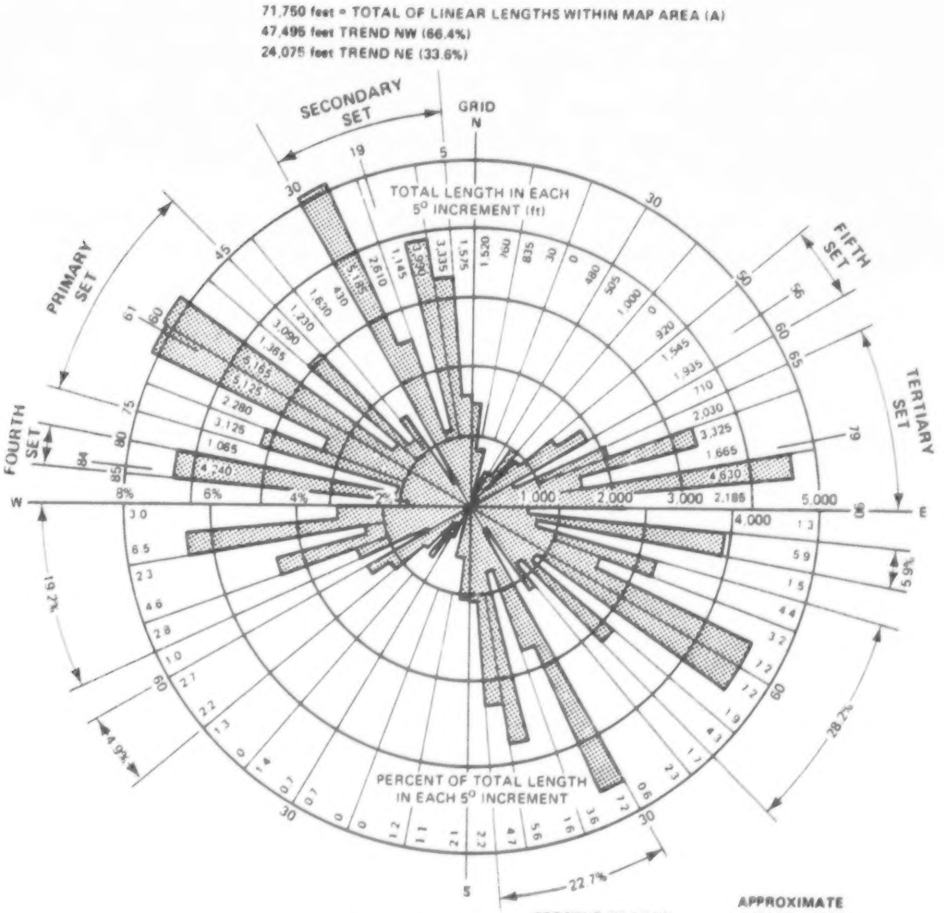


JOINT SET	JOINT STRIKE RANGE	 WTD. AVE.*	PERCENT OF TOTAL JOINTS MEASURED	APPROXIMATE RELATIVE JOINT FREQUENCY
PRIMARY	N40°-70°W	N52°W	54	5
SECONDARY	N20°-60°E	N35°E	19	2
TERTIARY	N10°-20°W	N12°W	19	2
			92	

*WTD. AVE. – WEIGHTED AVERAGE STRIKE (COMPASS DIRECTION) OF ALL JOINTS WITHIN THE SET.

SOURCE: DATA FROM RIO BLANCO OIL SHALE COMPANY

Figure 17. Rose diagram of surface joint strikes in vicinity of MDP area, Tract C-a (based on eight nearby outcrop stations).



LINEAR SET	STRIKE (B)		PERCENT OF TOTAL LINEAR LENGTHS MEASURED (D)		APPROXIMATE LINEAR LENGTH FREQUENCY (E)	
	RANGE	WTD. AVG. (C)				
PRIMARY	N45-75°W	N61°W	22.8		6	
SECONDARY	N5-30°W	N19°W	22.7		5	
SUBSET	N20-30°W	N26°W		10.8		2
SUBSET	N5-15°W	N12°W		10.3		2
TERTIARY	N65-90°E	N79°E	19.2		4	
SUBSET	N80-90°E	N86°E		9.5		2
SUBSET	N65-75°E	N71°E		7.4		1-2
FOURTH	N80-85°W	N84°W	5.9		1	
FIFTH	N50-60°E	N56°E	4.9		1	
			[illegible]			

NOTES

(A) MAP AREA OF RBOSC FIGURE MI-114

(B) REFERENCED FROM GRID NORTH (2°W OF TRUE NORTH)

(C) WEIGHTED BY LENGTHS OF ALL LINEARS WITHIN THE SET OR SUBSET

(D) PERCENT OF TOTAL LINEAR LENGTHS WITHIN MAP AREA (123 LINEARS WHOSE COMBINED LENGTH IS 71,570 feet)

(E) LINEAR SET PERCENTAGE COLUMN INDICATES APPROXIMATE RELATIVE LINEAR LENGTH FREQUENCY FOR EVERY 1 foot OF LINEAR LENGTH IN THE FOURTH AND FIFTH SETS, 6, 5, AND 4 feet ARE IN THE PRIMARY, SECONDARY, AND TERTIARY SETS, RESPECTIVELY

SOURCE R.A. HODGSON, GULF R&D, 1979)

Figure 18. Rose diagram of photolinear strikes within MDP area, Tract C-a (data from R.A. Hodgson, Gulf R&D, 1979).

is available, then the transmissivity parallel to the major flow axis (T_x), minor flow axis (T_y), and the storage coefficient (S) can be determined (see Figure 19). The procedure and equations developed by Hantush are as follows:

- Isotropic methods (Theis, Chow, Jacob) are used on each of the observation well rays to determine values for the effective transmissivity (T_e), S/T_1, and S/T_2, $T_e = \sqrt{(T_x)(T_y)}$.
- Parameters S/T_1 and S/T_2 are combined in Equation 3 to provide values of a and subsequently in Equation 4 to yield T_x and T_y

$$a = \frac{T_1}{T_n} = \frac{\cos^2(\theta+\alpha_n) + m \sin^2(\theta+\alpha_n)}{\cos^2\theta + m \sin^2\theta} \qquad (3)$$

where: T_n is the transmissivity in the direction $(\theta+\alpha)$ with the x-axis (Figure 19)

m is equal to

$$T_x/T_y = (T_e/T_y)^2 \quad . \qquad (4)$$

If $a_n = 1$, then Equations 3 and 4 can be combined:

$$m = \frac{T_e}{T_y} = \frac{a_n \cos^2\theta - \cos^2(\theta+\alpha_n)}{\sin^2(\theta+\alpha_n) - a_n \sin^2\theta} \qquad (5)$$

and m can be calculated because θ, α, a, and T_e are known. Substituting m into Equation 4 provides values of T_x and T_y.

- Values of T_1 and T_2 can be found by substituting m, θ, and α into Equation 6 and T_1 into Equation 3 to find T_2:

$$T_1 = T_x/(\cos 2\,\theta + m \sin 2\,\theta) \quad . \qquad (6)$$

- S is determined from the relationship S/T_1 and S/T_2 and should be essentially the same.

Principal direction of anisotropy not known (Hantush method)--If the principal direction of anisotropy is not known and there are at least three groups of observation stations on radial lines from the pumped well, then T_x, T_y, and S can be determined for the aquifer system. Figure 20 shows the required observation wells and some of the parameters used in the solution. The method presented by Hantush is as follows:

- Isotropic methods are used to determine T_e, S/T_1, S/T_2, and S/T_3 as discussed above.

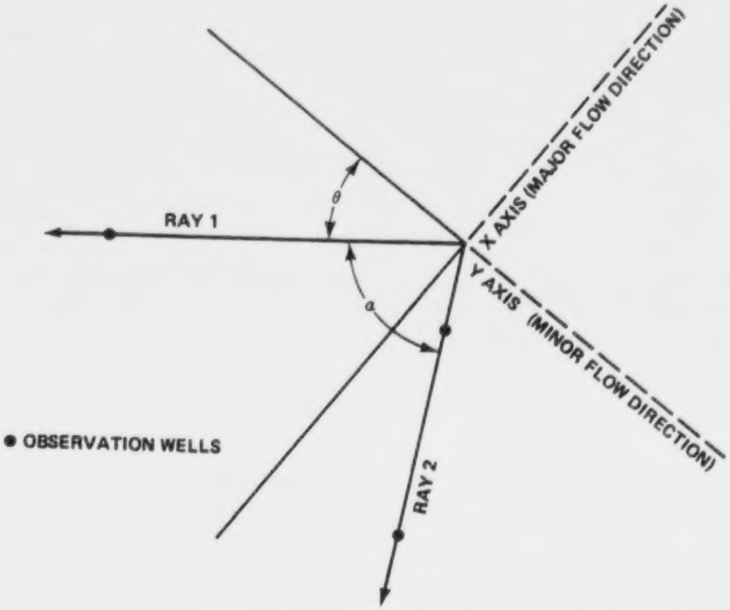

θ
RAY 1
X AXIS (MAJOR FLOW DIRECTION)
Y AXIS (MINOR FLOW DIRECTION)
α
● OBSERVATION WELLS
RAY 2

Figure 19. Illustration of parameters used by Hantush (1966) (known direction of anisotropy).

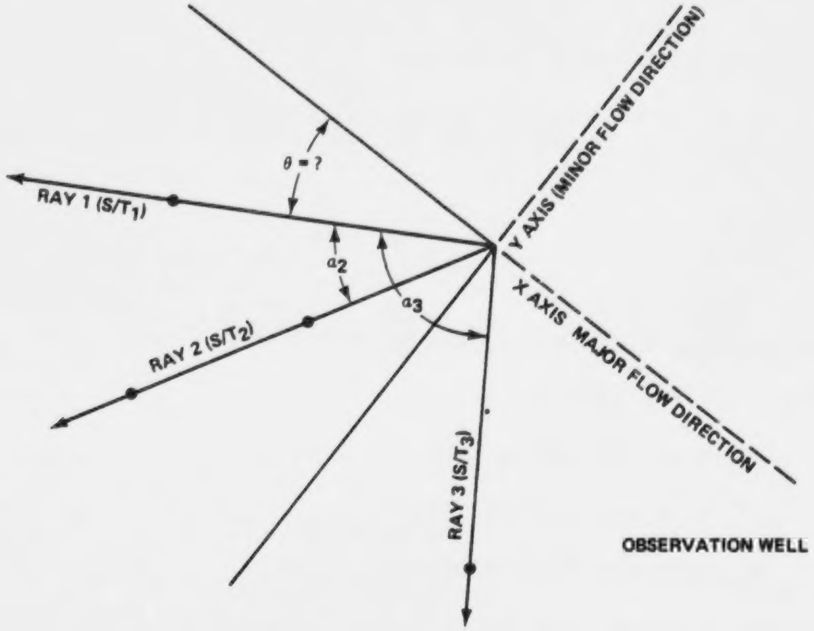

θ = ?
RAY 1 (S/T1)
Y AXIS (MINOR FLOW DIRECTION)
α2
α3
RAY 2 (S/T2)
X AXIS MAJOR FLOW DIRECTION
RAY 3 (S/T3)
OBSERVATION WELL

Figure 20. Illustration of parameters used by Hantush (1966) (unknown direction of anisotropy).

- S/T_1, S/T_2, and S/T_3 are combined in Equation 3 to determine a_2 and a_3. θ can be calculated from the following equation because α_2 and α_3 are known.

$$\tan(2\theta) = \frac{-2\ (a_3-1)\ \sin^2 \alpha_2 - (a_2-1)\ \sin^2 \alpha_3}{(a_3-1)\ \sin^2 \alpha_2 - (a_2-1)\ \sin^2 \alpha_3} \qquad (7)$$

- Substituting a_2, α_2, θ, and T_e into Equation 5 yields m, and T_1, T_2, and T_3 are found by substituting T_x, θ, m, α_2, α_3, and α_1 into the following formula:

$$T_n = T_x / \cos^2 (\theta+\alpha n) + m \sin^2 (\theta+\alpha n) \qquad (8)$$

- S is then calculated from the relationship(s) S/T_1, S/T_2, and S/T_3 and should be essentially the same value.

Equal drawdown ellipse known (Hantush-Thomas)--Hantush and Thomas (1966) have shown that if the effective transmissivity (T_e), the length of the major flow axis (a_2), and the length of the minor flow axis (b_s) are known for an anisotropic aquifer, then S, T_x, and T_y can be calculated. To utilize this method, sufficient observation stations are required such that equal drawdown ellipses can be constructed about the test well. Analytical methods and equations presented by Hantush and Thomas are as follows:

- Isotropic methods are used to determine T_e and S/t for each ray containing observation well(s).

- T_e is substituted into the formula(s) presented by Hantush (1966) and drawdown (s) is calculated for any distance along a given radii for the desired time.

$$s = \frac{Q}{4\pi(T_e)}\ W(u') \qquad (9)$$

from Equation 4, T_x and T_y can be determined.

where $u' = r^2 S/4t(T_n)$

r is the radius from the test well

t is the desired time

W(u') is the "well function"

- From the s values, one or more equal drawdown ellipses are constructed and a_s and b_s are determined (note: if there are sufficient observation points, the equal drawdown ellipses can be constructed from field data).

- T_x, T_y, and T_n are calculated using the following relationships:

$$T_x = a_s/b_s\ (T_e) \tag{10}$$

$$T_y = b_s/a_s\ (T_e) \tag{11}$$

$$T_n = r_n^2/a_s b_s\ (T_e) \tag{12}$$

- The "well function" of $W(u')$ is found using T_e, a specific drawdown (s) ellipse, and a modification of Equation 9

$$W(u') = \frac{4\pi s(T_e)}{Q} \quad . \tag{13}$$

Corresponding values of u' are found in tables presented by Walton (1962) and S is computed from the following relationship:

$$u' = \frac{a_s\ b_s\ S}{4(T_e)\ t_s} = \frac{r^2 S}{4(T_n)\ t} \quad . \tag{14}$$

Vertical hydraulic conductivity (leakage) for the Federal tracts has been calculated through a computer solution for the Neuman-Witherspoon leaky aquifer equation (Neuman and Witherspoon, 1969). If individual permeable zones within the Upper or Lower Aquifer systems are being evaluated (single or dual packer tests), leakage becomes a more important parameter and semiconfined aquifer conditions more accurately model field conditions. The analytical methods can be modified for semiconfined conditions by including the leakage factor (L). This is accomplished by modifying Equation 3 as follows:

$$a_n = \frac{T_1}{T_n} = \left(\frac{L_1}{L_n}\right)^2 = \frac{\cos^2(\theta+\alpha_n) + m\sin^2(\theta+\alpha_n)}{\cos^2\theta + m\sin^2} \tag{15}$$

where $L_n = T_n c$ (c is a constant). The procedure is the same as above except that Equation 15 replaces Equation 3 and isotropic semiconfined methods are used to calculate T_e and S/T_n.

Remarks--

Anisotropic flow patterns controlled by major fracture systems have been analyzed by tract developers using the R.E. Glover method and reevaluated by Kaman Tempo using a technique described by Kruseman and Ridder (1976). This analysis is discussed in Slawson (1980b). The long-term pump tests conducted on Tract C-b, the analytical methods, and recommendations for test modifications are also documented therein.

EVALUATION OF MINE DEVELOPMENT DATA

The third category of methods to obtain hydrogeologic data is evaluation of mine development data. Primary data sources contained within this category consist of those compiled from the existing monitoring program and ongoing mine construction. The results of baseline data collection programs on Lease Tracts C-a and C-b are presented in Sections 5 and 6 (pages 51-128) of a companion report entitled Monitoring Groundwater Quality: The Impact of In Situ Oil Shale Retorting (EPA-600/7-80-132). Evaluation of the existing monitoring program and data compiled therein is discussed in detail in Section 9 (pages 150-185) of that report.

As mine workings are developed, a perspective of the rock fracture and/or solution cavity system(s) can be gained, which can greatly supplement the data obtained in the two previous categories (geophysical methods and well testing procedures). For example, detailed surface geological surveys and analysis of photolinear strikes have been used to define anisotropic conditions that will affect long-term pump tests. These data are presented earlier in this section. Additional information can be gained by examining and mapping fracture surfaces encountered during mine development, observing and recording relative amounts of water entering the mine in different zones and areas, and sampling the quality of such water encountered.

The concept of mine development activities done in conjunction with hydrogeologic assessment offers a unique opportunity to conduct studies such as the dewatering and reinjection programs conducted at Federal Tracts C-a and C-b. Unfortunately, no record was kept of the quantities or quality of waters transported during these programs and therefore assessment of their utility in defining the hydrogeologic framework could not be made.

SECTION 4

SAMPLING METHODS

This section addresses the sampling methods currently being utilized in the oil shale region. Factors that influence the sampling methods are also discussed. These factors include well construction, sample handling, and preservation techniques.

WELL CONSTRUCTION FACTORS

The groundwater hydrology in the oil shale region can be significantly affected by the stratigraphy and structure of the area. Therefore, it is important to develop a site-specific characterization of the hydrogeology prior to the development of well specifications for a groundwater quality monitoring program. The purpose of this characterization work is to identify intervals of distinct water quality and hydraulic character. It is cost-effective to coordinate this hydrogeologic analysis with the preliminary resource exploration and evaluation efforts.

In addition to the hydrogeologic considerations, monitoring needs are an important consideration. Each well should be located and designed according to the objectives of an overall monitoring strategy. For instance, wells needed exclusively for piezometric measurements require accessibility only for water-level measuring instruments and should be designed with a minimum inner diameter. The need to collect water quality data or to conduct pump or injection tests dictate a different well design, as do wells monitoring two or more aquifers (i.e., multicompletion wells).

Preliminary site-specific characterization of the hydrogeology and objective analysis of the data requirements are essential to proper well design procedures. If this type of approach is utilized, both costly and timely well recompletion efforts will be avoided.

Discussed below are some aspects of well design and construction that should also be considered prior to implementation of a groundwater quality monitoring program.

Well Construction

Open Well or Perforated Over Entire Aquifer--

This type of well construction is common in the oil shale region. When the rock is well consolidated and competent, such in as the Lower Aquifer, the well is left open. In the Upper Aquifer wells, where tubing is usually perforated over the entire interval to maintain accessibility, caving is still a problem when semiconsolidated rock is intercepted by the well. Both types of well construction are designed to monitor a single vertical interval, in this case the entire Lower or Upper Aquifer.

Although this type of construction is commonly utilized for groundwater quality monitoring in the Piceance Basin, there are some disadvantages associated with the design. The regional hydrogeologic concept of a dual aquifer system (i.e., Upper and Lower) separated by the relatively impermeable Mahogany Zone has resulted in this design. However, on a smaller scale, the groundwater hydrology is more complicated. It has been shown that the deep aquifer of the oil shale region is actually composed of numerous fractures and cavities (i.e., secondary porosity) that will contribute variable water quality to a well completed over the entire interval. A sample collected from this well may reflect the composite water quality of the entire section or the water quality of a high head interval. In any case, the sample may not represent the true groundwater quality for a given aquifer. A potential pollutant of low concentration present in this situation may become diluted below detection limits in a composite sample, or it may not be detected at all in samples collected from an aquifer dominating the open section (i.e., a high head interval). In addition, a well completed over the entire section may not provide any information on the source of the contaminant.

In addition to water quality considerations, the hydraulic characteristics (e.g., transmissivity) of the different aquifer intervals are difficult to determine with this type of well design. Although an aquifer test will provide composite information on all of the aquifer intervals, the test procedure, without elaborate and costly modification, would be inconclusive for specific aquifer intervals. Furthermore, the interconnection of these different aquifer intervals can result in the collection of water quality samples from a layer exhibiting greater head rather than a composite including the adjacent layers.

Multiple Completion Wells--

Multiple completion wells are designed to monitor more than one aquifer interval (see Figure 21). The wells of this type in the Piceance Basin have two to four tubing strings per well, each of which are perforated in a specific aquifer interval. Potential interconnection among the different aquifers is prevented by the placement of cement grout in the annulus above and/or below the perforated zone and in some cases by bridging plugs used in conjunction with cement. This type of well construction is designed to minimize the problem of nondelineation of the vertical distribution of groundwater quality and hydraulic characteristics exhibited by the different layers within the Lower and Upper Aquifer zones.

Although this type of well construction provides for more representative sample collection from the various horizons, there are some problems associated with the present design utilized in the region. These problems include:

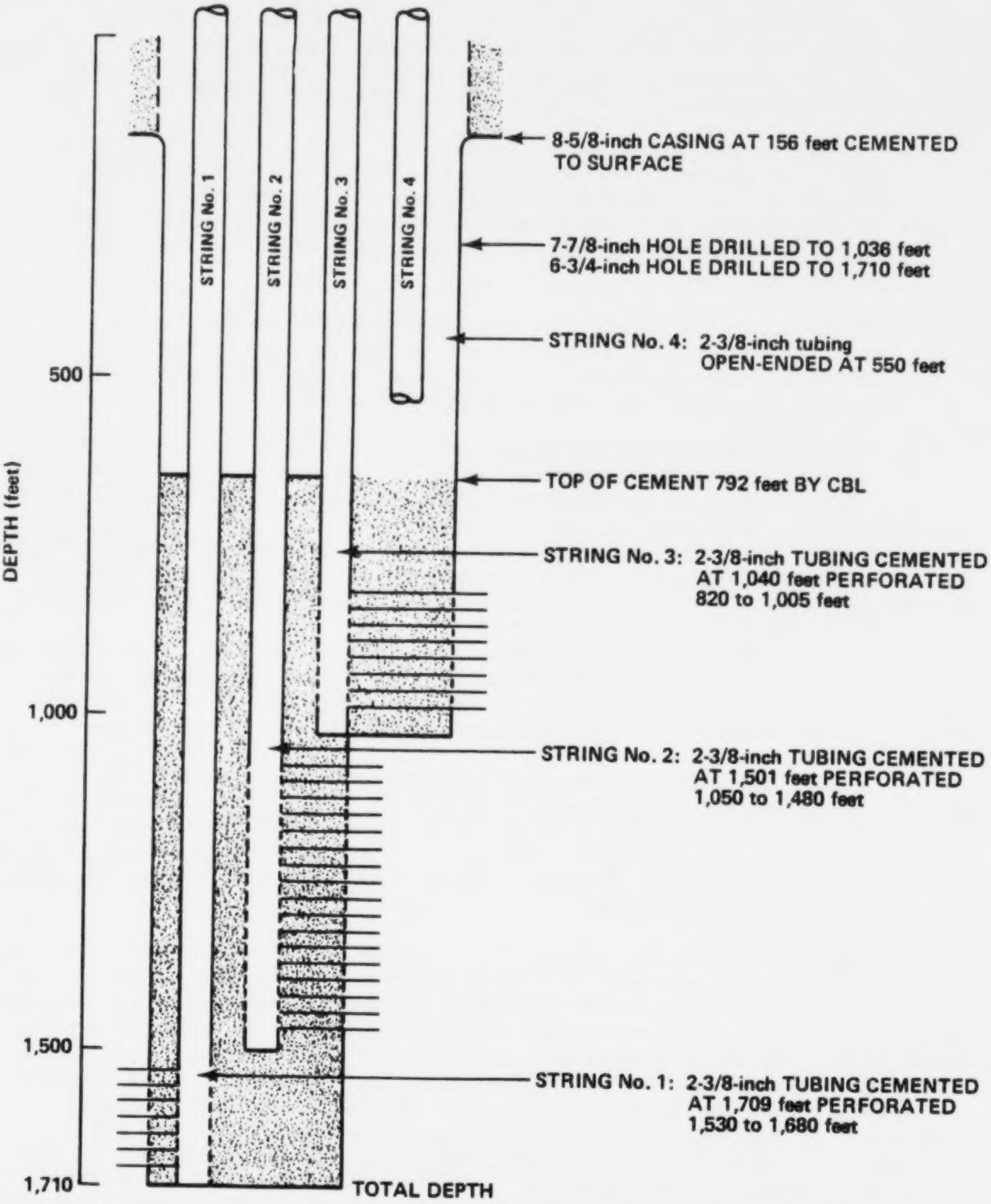

DEPTH (feet)
500
1,000
1,500
1,710
STRING No. 1
STRING No. 2
STRING No. 3
STRING No. 4
8-5/8-inch CASING AT 156 feet CEMENTED TO SURFACE
7-7/8-inch HOLE DRILLED TO 1,036 feet
6-3/4-inch HOLE DRILLED TO 1,710 feet
STRING No. 4: 2-3/8-inch tubing OPEN-ENDED AT 550 feet
TOP OF CEMENT 792 feet BY CBL
STRING No. 3: 2-3/8-inch TUBING CEMENTED AT 1,040 feet PERFORATED 820 to 1,005 feet
STRING No. 2: 2-3/8-inch TUBING CEMENTED AT 1,501 feet PERFORATED 1,050 to 1,480 feet
STRING No. 1: 2-3/8-inch TUBING CEMENTED AT 1,709 feet PERFORATED 1,530 to 1,680 feet
TOTAL DEPTH

Figure 21. An example of multiple completion well, Tract C-b Well SG-21.

- From a technical standpoint, pumping is the preferred method for assuring the collection of representative samples. Because the diameter of the tubing strings in these multiple completion wells will not accommodate a submersible pump, this type of well design is not recommended in the groundwater monitoring network.

- Although cement grout and bridging plugs are utilized, it is difficult to completely ensure that interconnection will not occur between different aquifer intervals using these techniques. If interconnection does occur, water quality samples collected from the well may be nonrepresentative and costly recompletion efforts may be required.

- The structural properties of the small-diameter tubing strings are, in some settings, insufficient at the depths required for monitoring deep aquifers. Failure of a tubing string can result in very expensive and time-consuming replacement.

It should be noted that the above referenced groundwater monitoring system was derived from a well recompletion effort conducted on a tract in the Piceance Basin. Many of the problems cited are due to the well design prior to recompletion (e.g., the 2-5/8-inch tubing strings). It is strongly recommended that future multiple completion designs be modified to allow for 6-inch diameter wells. This aspect would not only provide for sample collection by pumping but also significantly reduce potential failure of a well at depth.

To accommodate a submersible pump for sample collection, larger-diameter boreholes are required for installation of the larger diameter, multiple completion wells. The borehole should be drilled large enough to accommodate the casing, 6-inch-diameter well strings, and cement grout. These proposed well specifications require an annulus of 10 to 12 inches. The cost implications (in 1980 dollars) of this increase in diameter are substantial during the initial drilling operation, on the order of \$26 to \$30 per foot. Casing costs are estimated (in 1980 dollars) to be in the range of \$10 to \$13 per foot. Drilling, casing, and equipment costs can be obtained for comparison purposes in Everett et al. (1976). In Everett et al. (1976), a methodology for updating the 1976 costs is provided.

Although the costs are substantially higher for the multiple, 6-inch well design, the sampling approach is more effective compared to the smaller diameter tubing strings. The common procedure for sampling these smaller diameter wells is a bailer, which represents a passive method of groundwater quality monitoring. The effectiveness of a well in providing baseline water quality data and/or detecting potential pollutant excursions using bailing techniques is dependent upon the location of the well and the hydrologic gradient. In comparison to pumping, the passive nature of a monitoring program utilizing bailing as a sample collection method requires an additional number of wells to be incorporated in the network. The larger diameter wells allow samples to be collected by pumping. Since pumping samples a larger cross-sectional area of the aquifer, fewer wells are required in the monitoring program. The active nature of this sampling approach will also allow the detection of any potential pollutants present in the zone of groundwater flow intercepted by the pumping.

Well Size

The diameter of the monitoring well should be large enough to accommodate the sampling tool. Where a submersible pump is to be utilized in deep aquifers, the well diameter should be at least 6 inches. For shallower alluvial wells, a 4-inch-diameter well is adequate to accommodate a submersible pump. Wells from which water-level measurements are required need only be 1 inch in diameter.

The diameter of the borehole into which the casing is placed must be at least large enough for proper casing placement. It is recommended that the borehole be at least 2 inches larger than the casing in the multiple completion wells to permit proper placement of the cement grout around the casing and adjacent to the layers or aquifers that are to be sealed from the well.

The approximate costs of drilling, casing, grout placement, etc. are provided in the discussion on well construction above.

Annular Seal

The annular space consists of the area between the casing material and the borehole. This space is unavoidable regardless of the drilling method or casing installation. To prevent contamination of the well from surface drainage or from formations other than the aquifer to be monitored, this annular space should be sealed.

The most common material used in providing an annular seal is cement grout. Cement grout is a fluid slurry composed of a mixture of Portland cement and water. The ratio of water to cement for a suitable grout mixture is 5 to 6 gallons of water per 90 pounds of cement (Johnson Division, 1966). Mixtures of more than 6 gallons of water to 90 pounds of cement should not be used because the amount of shrinkage upon settling increases with water content, producing an inadequate annular seal. In addition, the water used for the grout should be free of oil or other organic material, dissolved solids content should be less than 2,000 mg/l, and the sulfate content should be kept to a minimum.

The correct placement of the cement grout is equally as important as its composition. To assure that the grout will provide a satisfactory seal against potential pollutants from the surface or aquifers not to be incorporated in the monitoring well, implacement should be continuous with the cement slurry introduced through a pipe 2 to 4 inches in diameter. Introducing the grout through a pipe to the desired depth will prevent any gravitational separation of the cement due to "free falling." This aspect is particularly important in the deep aquifer wells where the grout may have to be placed at great depths to prevent aquifer interconnection.

Casing Material

Well casing materials can play a critical role in a groundwater quality monitoring well. The potential influence of the casing material on groundwater chemistry, the structural properties of the well, and economics of the monitoring program are all important considerations. In general, the proper selection of casing requires site-specific evaluation of the monitoring objectives, groundwater characteristics, and the anticipated well specifications. Some properties of various well casing materials that should be considered and evaluated prior to installation are presented below.

Plastic Casing and Screens--

Plastic well casing is widely utilized in groundwater monitoring wells, particularly at shallow depths. The most common type of plastic casing used is polyvinyl chloride (PVC).

The primary advantages associated with PVC casing include:

- Nonconducting -- electrochemical reactions will not be a factor affecting the groundwater quality
- Inert -- resists chemical attack (with the exception of ketones, esters, and aromatics (U.S. EPA, 1977)
- Lightweight -- easy to handle and install
- Inexpensive when compared to other casing materials (i.e., steel and stainless steel) -- if the previous recommendations are followed (i.e., 6-5/8-inch-diameter wells), the PVC should be at least schedule 40 (19/64 inch) in thickness; with these specifications the PVC would cost approximately $2.50 to $3.00 per foot (Everett et al., 1976).

The disadvantages associated with PVC casing include:

- The structural properties of PVC may be inadequate at depth. Given the well consolidated rock in the oil shale region, this should not be a great problem provided the casing is installed correctly and the pipe schedule is selected properly.
- If PVC is cemented together, organic solvents will be introduced into the groundwater system, resulting in anomalous trace organic determinations. To alleviate this problem, it is suggested that pressure joints be used for PVC connections.
- PVC possesses a hydrophobic surface when initially introduced into the groundwater system, causing trace organics to be extracted from the groundwater until equilibrium between the PVC and the groundwater system is reached.

Steel Casing and Perforated Tubing--

Steel casing and perforated tubing is widely used in the deep aquifer wells of the Piceance Basin. The basic disadvantages of utilizing steel materials in a well are:

- Steel casing and tubing materials are active conductors and will be involved in electrochemical reactions, in most cases causing the plating of iron (although iron can go into solution as well).
- Steel materials can contaminate water quality samples collected from the well through the introduction of trace metals derived from the casing or tubing. Also, the sorption of trace metals or organic constituents may occur due to metal oxides.
- In the Piceance Basin, perforated steel tubing commonly has to be replaced due to the corrosive groundwater environment, which is a costly procedure. Excessive corrosion can result in nonrepresentative samples being collected from the well.
- The structural properties of the small, 2-5/8-inch perforated tubing strings are, in some cases, not sufficient to withstand deep aquifer conditions. In this situation, the tubing will fail and accessibility to the well will not be maintained.
- Steel materials cost approximately $1 to $1.75 more per foot than PVC.
- Steel materials can be more difficult to handle.

Many of these disadvantages are due to the restricted well diameters. If the inner diameter of the wells were expanded to 6 inches, nonpumping sampling techniques could be discontinued. In addition, the collection of groundwater samples that reflect the effects of the steel casing material would be minimized, provided the well is flushed prior to sample collection. Failure of the wells can also be significantly reduced, if not completely eliminated, with the increased diameter.

Stainless Steel Casing and Screens--

Stainless steel materials technically surpass any material for groundwater quality monitoring purposes. They are inert to all chemical reactions and will not contaminate the groundwater environment. Furthermore, stainless steel materials are structurally stable under any conditions if selected properly.

The major detriment to installing stainless steel materials in monitoring wells is the cost. Stainless steel screen generally costs between $25 and $35 per foot, significantly more than other casing materials. The advantages of the stainless steel material do not compensate for the economics, particularly when the disadvantages associated with the other materials can be mitigated if correct sampling procedures are followed.

Well Security and Protection

As with any well, proper procedures should be taken to ensure the protection and security of the monitoring well after installation. These procedures will prevent the inadvertent or deliberate introduction of materials into the well. Proper protection will also deny accessibility to small rodents. These foreign materials can notably affect the groundwater quality data obtained from the well, particularly if nonpumping sampling techniques are practiced.

Well security can be best acquired by placing a locking cap on the well. If continuous monitoring equipment (e.g., Stevens Water Level Recorder) is employed, it should be protected as well. This can usually be done by welding a metal box with hinges onto the well casing and installing a lock on the metal box.

WELL DESIGN AND SAMPLING COSTS

Well Design Costs

Approximate costs for each well design are provided below. These costs assume that 24 sites were selected for each well design. This assumption provides for a per-well distribution of the base costs that are accrued by a multiple drilling operation. Such base costs include capital requirements for mobilizing drilling equipment to the region, contracting geophysical equipment on a monthly basis, and delivery of materials (i.e., tubing strings, casing, packers, etc.) to the site.

The costs provided below assume that the number of wells were evenly distributed among the Upper and Lower Aquifer. For instance, the Tract C-a design would have 12 dual completion wells montoring both the Upper and Lower Aquifer (see Figure 22), whereas the U.S. Geological Survey (USGS) approach is to construct 2 wells per site (see Figure 23), one in the Upper Aquifer and one in the Lower Aquifer. This distribution will assure comparable well costs for each approach since there are the same number of wells in each aquifer.

The approximate costs of each well design are as follows:

Design	Approximate cost per well (dollars)	Approximate cost per site (dollars)
USGS		
Upper Aquifer well	18,000-20,000	53,000-58,000
Lower Aquifer well	35,000-38,000	
Tract C-a		
Dual completion well	35,500-38,000	35,500-38,000
Tract C-b		
Multiple completion well	39,000-44,000	39,000-44,000

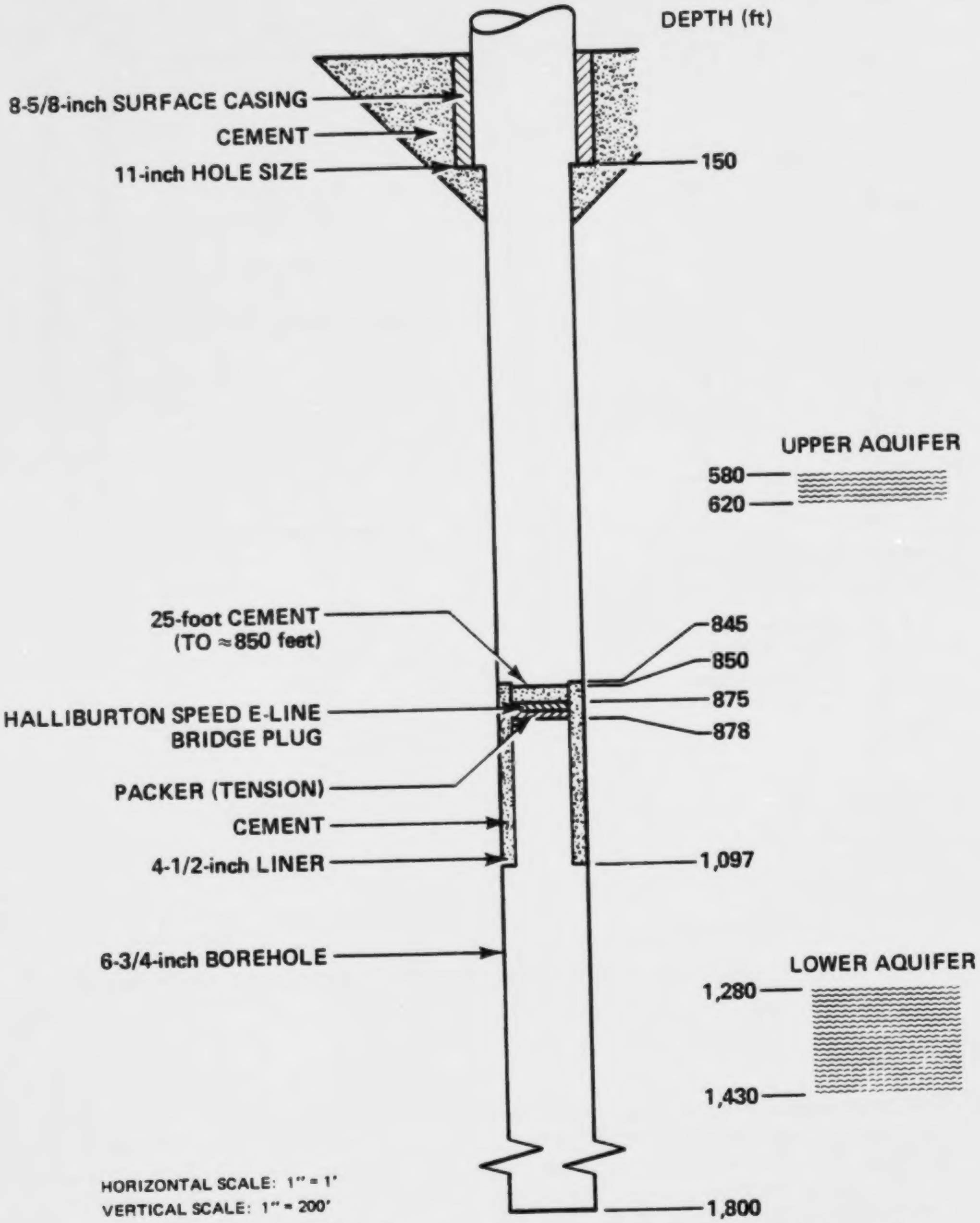

DEPTH (ft)
8-5/8-inch SURFACE CASING
CEMENT
11-inch HOLE SIZE
150
UPPER AQUIFER
580
620
25-foot CEMENT (TO ≈850 feet)
845
850
875
878
HALLIBURTON SPEED E-LINE BRIDGE PLUG
PACKER (TENSION)
CEMENT
4-1/2-inch LINER
1,097
6-3/4-inch BOREHOLE
LOWER AQUIFER
1,280
1,430
HORIZONTAL SCALE: 1" = 1'
VERTICAL SCALE: 1" = 200'
1,800

Figure 22. Typical recompleted Upper Aquifer monitoring well for Tract C-a (derived from Rio Blanco Oil Shale Co., March 1979).

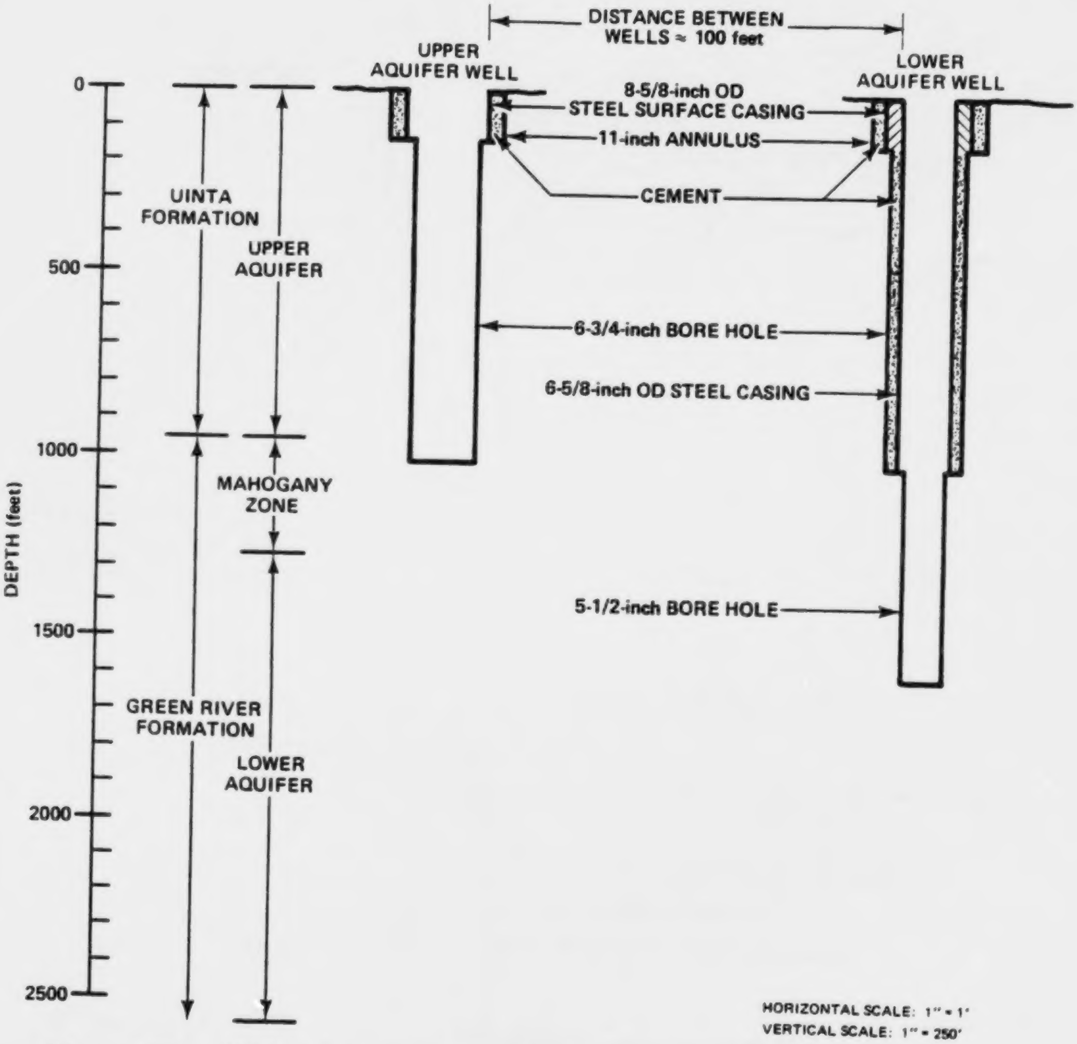

DISTANCE BETWEEN WELLS ≈ 100 feet
UPPER AQUIFER WELL
LOWER AQUIFER WELL
8-5/8-inch OD STEEL SURFACE CASING
11-inch ANNULUS
CEMENT
6-3/4-inch BORE HOLE
6-5/8-inch OD STEEL CASING
5-1/2-inch BORE HOLE
0
500
1000
1500
2000
2500
DEPTH (feet)
UINTA FORMATION
UPPER AQUIFER
MAHOGANY ZONE
GREEN RIVER FORMATION
LOWER AQUIFER
HORIZONTAL SCALE: 1" = 1'
VERTICAL SCALE: 1" = 250'

Figure 23. USGS Upper and Lower Aquifer monitoring well design.

Sampling Costs

The approximate sampling costs for each well design and corresponding sampling method are presented in the subsection that follows ("Sample Collection Methods"). In addition to the sampling methods currently being utilized in the oil shale region (i.e., bailing, swabbing, and portable submersible pump), a fixed submersible pump was analyzed as a sampling approach. For comparison purposes, the costs for each sampling method were developed under the assumption of a quarterly sampling frequency of 12 Upper and Lower Aquifer wells for a 5-year period. Sampling costs include the wages for personnel, the materials utilized, and equipment capital requirements.

The sampling costs and corresponding well design costs (derived from well design cost data presented above) are given in Table 13. Based on the data presented in Table 13, it is apparent that the bailing method is the best approach from a cost perspective. The portable submersible pump and swabbing methods are very expensive compared to the bailing method and, therefore, are not recommended. Although the fixed submersible pump is more expensive to utilize than bailing, this method should not be ruled out due to the technical advantages of the approach. Each method is discussed further in the discussion of "Sample Collection Methods" (below).

The initial step in developing the well construction costs was to identify the specifications for each design. The costs for the drilling operations, geophysical logging, and materials relative to each of the design specifications was provided by companies dealing in these areas. Three companies were contacted for each of these areas and average costs were developed. These construction costs were then reconfirmed by the respective designers (i.e., USGS, Tract C-a developers, and Tract C-b developers).

In most cases, the sampling costs were provided through correspondence with USGS, Tract C-a developers, and Tract C-b developers. The costs that were not included in this correspondence were developed in a similar manner to the well construction costs.

MONITOR WELL PLACEMENT

The placement and design of monitoring wells is defined by the design of the MIS operation, the site-specific hydrogeology, and by the potential mobility of the constituents from the MIS retorts. An earlier companion report (Slawson, 1980a) examined proposed monitoring programs for Federal Oil Shale Tracts U-a and U-b to identify information deficiencies and to develop a monitoring design program. Monitor well program designs are developed for different aspects of the MIS mining operations. Specific examples are presented that show monitor well placement for proposed and existing alluvial, Bird's Nest, and Douglas Creek aquifers. Additional wells are identified in the saturated zone of the Uinta and Green River Formations above the Bird's Nest aquifer. Source specific monitoring systems for spent shale landfills include observation wells and multiple completion wells, as well as geophysical and unsaturated sediment monitoring devices. For greater detail on monitor well placement, see Slawson (1980a), entitled Groundwater Quality Monitoring of Western Oil Shale Development: Monitoring Program Development.

SAMPLE COLLECTION METHODS

Three predominant methods of sample collection are commonly utilized in the oil shale region: bailing, swabbing, and pumping. Each of these sampling procedures is discussed below with respect to advantages and disadvantages of the methodology, as well as the approximate costs for initiating and conducting each procedure. Related issues, i.e., quality and custody control of the water quality samples obtained, are discussed by Everett (1980) and Slawson (1980b).

TABLE 13. SAMPLING COSTS

Item	Fixed Submersible Pump	Portable Submersible Pump (USGS)	Bailing (Tract C-a)	Swabbing (Tract C-b)
Well Construction	53,000-58,000[a]	53,000-58,000	35,500-38,000	39,000-44,000
Sampling Costs				
Capital Requirements	61,800-79,800	55,000-60,000	8,000-10,000	N/A[b]
Operational Requirements (Quarterly)	200-400	1,400-1,700	200-400	16,000-18,000
Labor (quarterly)	135-200[c]	11,200-14,000[d]	135-200[c]	3,500-4,300[e]
Five-year Total (including construction of 12 monitoring well sites)	704,500-787,800	943,000-1,072,000	440,700-478,000	858,000-974,000

Notes:

All costs in 1980 dollars.

[a] Assumes similar well construction for fixed pump as with portable pump.

[b] Tract C-b contracts swabbing rig, thereby eliminating capital requirements.

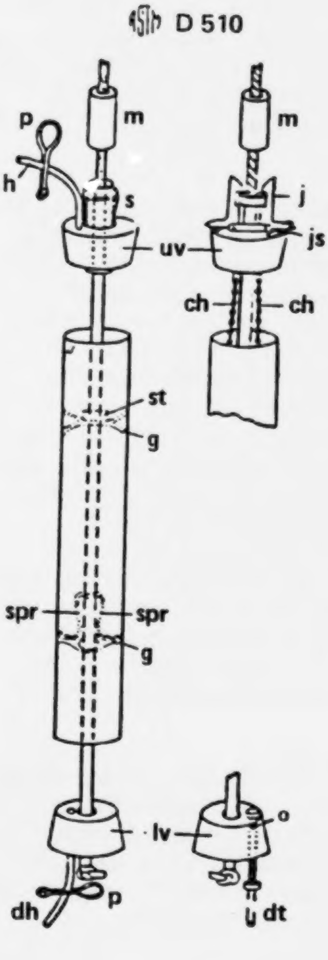
[c] Assumes the sampling of eight wells per day.

[d] Assumes sampling of one well per day.

[e] Assumes the sampling of three wells per day.

Bailing

Bailing involves introducing a hollow cylinder that is supported from the surface into the well. Figure 24 portrays the features of a Kemmerer sampler, a commonly used bailer. The cylinder can be tripped to close at any desired depth thereby collecting a sample. The important aspect of the Kemmerer sampler is that it allows the water to flow through the cylinder, thus permitting samples to be collected from any depth. Samplers that are open at the top and sealed at the bottom do not have this flow-through characteristic and should not be used because the sampler is generally filled with the first water encountered in the well, i.e., the water near the static water level.



ch	**Chain that anchors upper valve to upper interior guide**
dh	**Rubber drain tube**
dt	**Brass drain tube**
g	**Interior guide fastened to inner surface of sampler**
h	**Rubber tube**
j	**Jaw of release**
js	**Jaw spring**
lv	**Lower valve**
m	**Messenger**
o	**Opening interior of drain tube**
p	**Pinch cock**
s	**Upper release spring operating on horizontal pin, one end of which fits into groove on central rod**
spr	**Spring fastened to lower internal guide and operating in groove on central rod to provide lower release**
st	**Stop on central rod**
uv	**Upper valve**

Left: View of complete sampler with valves open

Top Right: Another type of construction of upper valve and tripping device

Bottom Right: Another type of construction of lower valve and drain tube

Figure 24. Features of the modified Kemmerer bailer (P.S. Welch, Limnological Methods, p. 200, Figure 59).

The major advantage of utilizing the bailing method is that it allows samples to be collected from small-diameter wells that have relatively deep static water levels, a situation that generally restricts the use of other sampling methods. Bailing is also very simple to use and does not require a large number of personnel for operation. It is also fairly inexpensive, with capital requirements (i.e., bailer, winch, power source, truck, etc.) of $8,000 to $10,000 (in 1980 dollars).

There are a number of potential problems associated with bailing water quality samples. Extreme variations in the water quality data can be observed when the depth selected for sampling is inconsistent. This is pronounced when the well is completed in an aquifer possessing multiple permeable intervals, which may contribute dissimilar water quality. The groundwater in such wells can be stratified, resulting in noticeable vertical changes in water quality. Schmidt (1977) attributes this stratification to the distinct water quality in each permeable zone penetrated by the well. Schmidt (1977) also suggests that variations in the composition of aquifer materials with depth and possible differences in the sources of recharge can modify groundwater quality in wells penetrating these intervals.

An additional problem is the nonrepresentative nature of the sample collected. Water standing in the well bore above the screened or open interval will be isolated and have little or no mixing with natural groundwater. This stagnation effect is particularly pronounced in little-used or nonpumping wells. Samples collected from this stagnant zone are not indicative of the groundwater quality and will result in unrepresentative data. Factors contributing to the unrepresentative nature of the samples collected from the well bore include the introduction of unnatural constituents through the interaction between the casing with the groundwater system, as well as foreign material entering the well from the surface. Furthermore, changes in pH, and subsequently in water quality, can be induced through the variations in pressure and CO_2 dissolution in the well bore (Summers and Brandvold, 1967).

The magnitude of the vertical variations that can be observed during sampling a well is shown in Figures 25, 26, and 27. These vertical profiles were compiled by collecting samples from specific depths via a bailer and performing specific conductance and temperature measurements for each sample. The results of the detailed water chemistry analysis for selected samples are shown in Table 14.

The temperature and conductivity profile for Well GS-13 (well diagrammed in Figure 28) show a declining level of conductivity over the approximately 375 feet of water standing in the well bore. The conductivity measurement obtained near the static water level was 2,300 µmho/cm, compared to a measurement of 1,600 µmho/cm obtained near the bottom of the open interval (see Figure 25). Temperature measurements were much more uniform with depth.

Appreciable increases in conductivity with depth were also noted in Wells D-17 and D-18 (Figures 26 and 27, respectively). In Well D-18, an order-of-magnitude increase in conductivity was observed in a very small interval near the bottom of the well. Above this level the conductivity was very stable. The decline in conductivity with depth noted in Well GS-13 is also seen in the

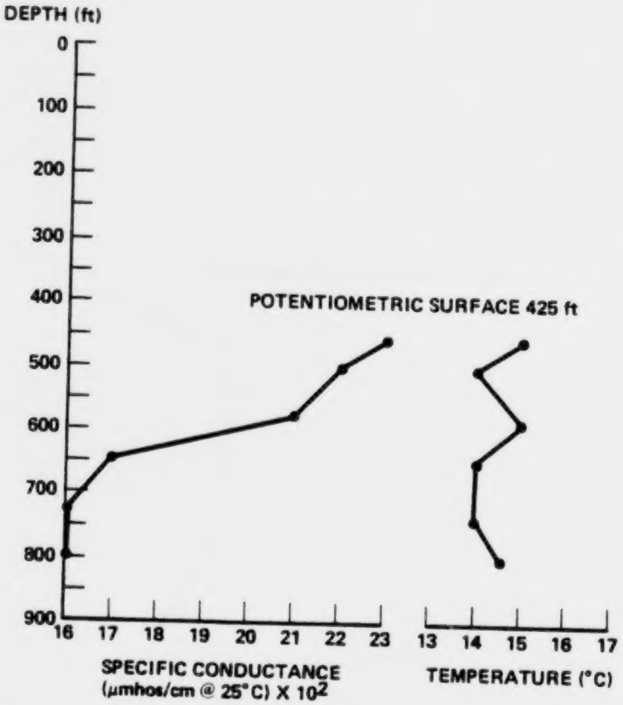


Figure 25. Variation in specific conductance and temperature with depth, Upper Aquifer Well GS-13, Tract C-a.

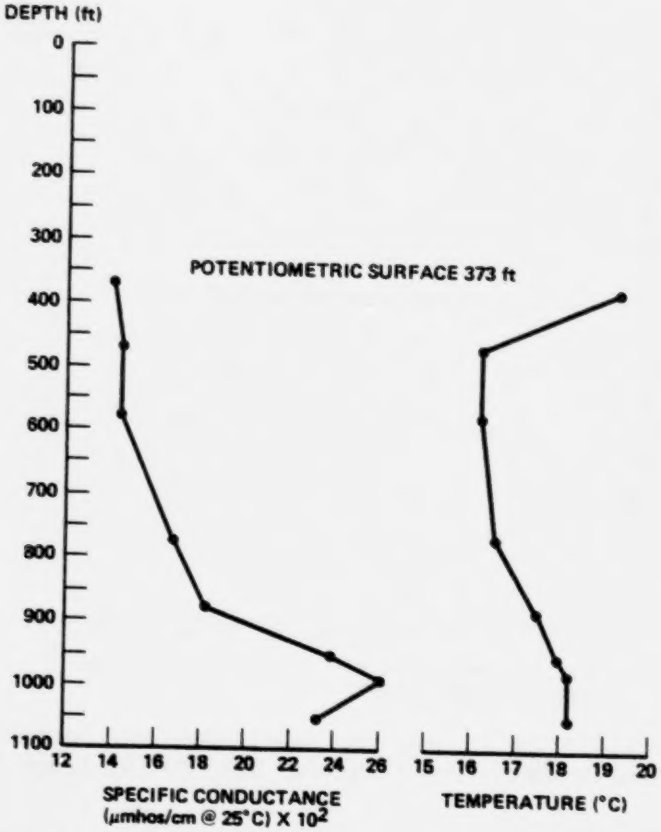


Figure 26. Variation in specific conductance and temperature with depth, Lower Aquifer Well D-17, Tract C-a.

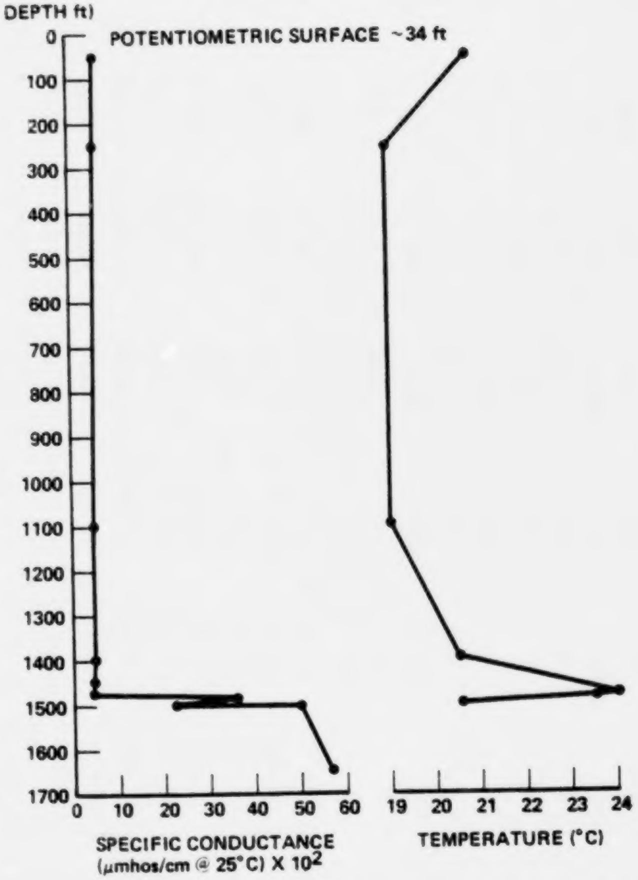


Figure 27. Variation in specific conductance and temperature with depth, Lower Aquifer Well D-18, Tract C-a.

TABLE 14. VARIATION IN WATER QUALITY WITH DEPTH IN SELECTED DEEP AQUIFER WELLS, TRACT C-a

Constituent[a]	Depth (feet)							
	Well GS-13			Well D-17			Well D-18	
	450	575	725	475	875	990	1,400	1,500
pH	7.3	7.5	7.5	9.1	9.0	8.6	8.2	8.1
Specific conductance	1,940	1,559	1,344	1,344	1,790	2,210	3,856	64,794
Total dissolved solids	1,409	1,140	1,160	1,093	1,174	1,524	2,954	37,839
Calcium	67	46	42	3.4	3.9	5.0	2.2	2.8
Magnesium	118	89	82	32	30	24	6.6	6.8
Sodium	281	213	194	372	417	557	1,224	16,816
Potassium	0.8	0.5	0.4	1.9	2.6	2.3	2.3	14.2
Bicarbonate	775	551	637	686	898	1,355	3,089	45,682
Carbonate	<1	<1	<1	8.8	13.1	4.8	<1	<1
Sulfate	610	466	262	304	170	118	97	220
Chloride	13.4	11.4	35.7	28.2	53.6	59.0	47.2	480
Fluoride	0.48	<0.1	<0.1	1.6	2.6	5.6	9.3	10.1
Ammonia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	3.9
Arsenic	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
Boron	0.29	0.31	0.31	0.31	0.53	0.73	0.79	0.87
Mercury	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Selenium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Dissolved organic carbon	28.6	30.6	27.2	24.1	35.0	25.7	12.4	21.0

Note:

[a] Constituent units are mg/l except for pH units and specific conductance in μmhos/cm at 25°C.

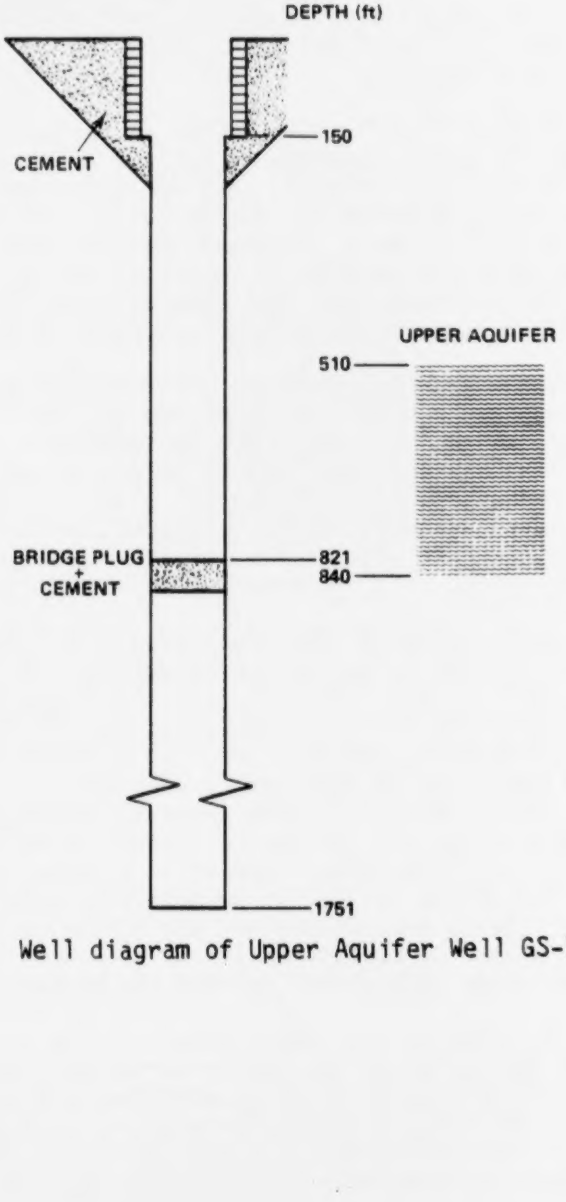

DEPTH (ft)
150
CEMENT
UPPER AQUIFER
510
BRIDGE PLUG + CEMENT
821
840
1751

Figure 28. Well diagram of Upper Aquifer Well GS-13, Tract C-a.

water chemistry data (Table 14). The largest changes with depth were observed for the major inorganic ions. The trace constituents and DOC were generally more stable with depth. The general ionic composition is fairly consistent at all three depths in Well GS-13, although sulfate concentrations decreased with depth to a greater extent than most other ions.

The increases in conductivity with depth observed in Wells D-17 and D-18 are also consistent with water chemistry analysis (Table 14). Most of the conductivity increase in Well D-17 can be attributed to increased sodium bicarbonate concentration. Magnesium, carbonate, and sulfate levels decline with depth. Thus, the salinity of the water increased and the ionic composition of the well water changed.

The variation in water quality with depth, as indicated in Figures 25, 26, and 27 and Table 14, demonstrate the importance of consistent sample collection depths. This is a very critical area and essential to accurate data interpretation. The depth selected for sample collection is of equal importance. It is obvious that a sample collected near the static water level or in the cased section above the aquifer is unrepresentative of the groundwater system. Therefore, it is recommended that samples be collected from the portion of the well that is screened or open and adjacent to the aquifer.

To collect a representative sample using the bailer method and to assure the above-cited effects are minimal, at least one well volume of water should be evacuated from shallow wells in which the groundwater movement is very slow. This is particularly important because stagnation effects can greatly influence the water quality of these low-yielding wells. Once one well volume has been removed, a representative sample can be obtained. In very-low-yielding wells where the evacuation process has resulted in dryness, the well should be allowed to recover prior to sample withdrawal.

Removal of one well volume is very impractical for eliminating stagnant water in a deep well with the bailer method because of the quantity of water obtainable from the well on each down-hole trip. Attempting to evacuate one or more well volumes would be very time-consuming and inefficient for the field personnel. As previously demonstrated, representative samples of the natural groundwater system can be obtained by sampling adjacent to the open or perforated section. Marsh and Lloyd (1980) have indicated that this is particularly true for wells that monitor aquifers where significant groundwater movement is occurring. If this type of approach is to be utilized, the hydraulic characteristics of the aquifer to be monitored should be determined. These characteristics can be best determined during the initial drilling operations. However, if postdrilling determinations are necessary, down-hole flowmeter surveys and other geophysical methods can be beneficial.

Additional modification of the sample chemistry can occur when transferring the sample from the bailer to the sample container. Precipitation of easily oxidized constituents by introducing atmospheric oxygen during the transfer and altering the natural oxidation-reduction potential is of primary concern. The loss of dissolved gases is also a potential problem during the transfer process. To alleviate the effects of the sample transfer, sample contact with the air should be minimized. Furthermore, caution should be taken when transferring the sample in order to prevent unnecessary agitation.

An additional consideration when sampling is the number of samples necessary to determine the difference among data collected during different sampling periods. To accurately address this consideration, the variability of the data needs to be established. To identify this variability, four replicate samples were collected from selected depths in four wells. The sampling program involved the (1) collection of field data (i.e., specific conductance, temperature, and pH) and (2) collection of samples for detailed chemical analysis.

The results of the statistical analysis indicate that only one sample is necessary for accurately determining a difference among data sets for the major constituents (e.g., bicarbonate, sodium, TDS). This is also true for constituents that are intermediate in concentration (e.g., sulfate, chloride). For the constituents that are low in concentration (.e.g, calcium, magnesium, fluoride, etc.), an extremely high number of samples appears to be required. However, this aspect can be attributed to the statistical procedure and it is therefore not necessary to collect more than one sample to characterize these constituents.

In summary, the following procedure is recommended for collecting samples from a well when using a bailer:

1. Use a flow-through type of bailer (e.g., Kemmerer sampler)
2. Compile well completion data; of particular importance is well diameter, depth to aquifer, aquifer thickness, and total depth
3. For shallow wells with very slow groundwater movement, estimate the well volume from the well completion data and extract at least one well volume previous to sample collection.
4. For both shallow and deep wells, select a sampling point adjacent to the aquifer
5. Consistently sample from the same depth and adjacent to the aquifer during every sampling effort
6. It is necessary to collect only one sample from the well
7. Measure temperature, specific conductance, and pH in the field.

Pumping

The use of a submersible pump is a common procedure for sample collection from the alluvial wells on Tract C-b and the deep wells monitored by the USGS. For this sampling method, the submersible pump is introduced to the desired depth and a sample collected from the discharge line. A typical pumping apparatus configuration is shown in Figure 29.

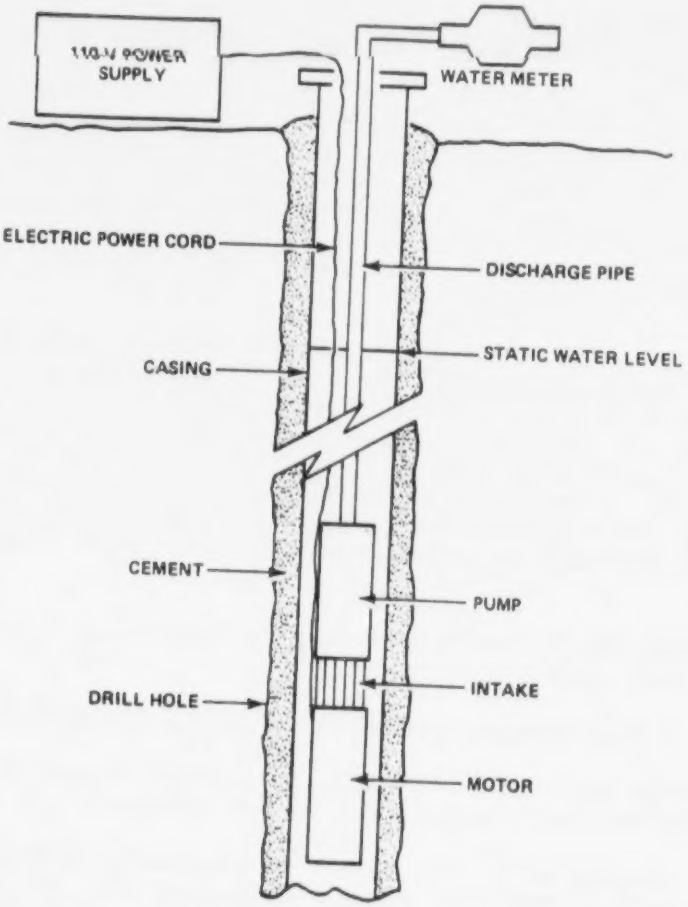

110-V POWER SUPPLY
WATER METER
ELECTRIC POWER CORD
DISCHARGE PIPE
CASING
STATIC WATER LEVEL
CEMENT
PUMP
DRILL HOLE
INTAKE
MOTOR

Figure 29. Typical pump apparatus configuration (after Slawson, 1980b).

The use of the submersible pump for sample collection is the superior sampling approach. Submersible pumps can be used to collect samples from any depth provided the pump is properly selected and the well is conducive to pumping. Submersible pumps can efficiently extract sufficient volumes of water and eliminate the stagnant well bore water, thereby allowing representative sample collection. Extraction can be performed in a relatively short period of time. Additional advantages of submersible pumps include:

- Easy installation and withdrawal from a shallow well (although a great deal of effort may be required for a deep well)
- Little maintenance is required

- They can be used as portable or fixed pumps; both Tract C-b and USGS personnel have designed a truck-portable pump capable of efficiently servicing a suite of wells

- The well discharge can be easily controlled and both very low or very high discharges can be obtained

- They have relatively little effect on the native aquifer water quality (nitrogen and airlift methods, however, can substantially alter the iron content and pH of the water and, therefore, are not recommended).

Although these characteristics make the submersible pump the preferred sampling approach, some aspects may preclude its use. The primary disadvantage of the submersible pump is the minimum size requirements of the well annulus. Submersible pumps generally require a minimum 4-inch-diameter well for shallow sampling efforts and a 6- to 8-inch-diameter well for deeper sampling. As most of the wells in the study area have 2-5/8-inch tubing in the deep wells, the use of a submersible pump in the sampling program is limited.

An additional disadvantage of this approach is the capital requirement, which can be significantly higher than other sampling devices. The Tract C-b truck-portable pump, which is capable of sampling at depths up to 100 feet, costs $10,000 to $12,000 in 1980. However, the USGS portable pump rig, which is designed to be set at depths of 500 to 600 feet (i.e., Upper Aquifer wells), requires an initial expenditure of $50,000 to $60,000. Rigs designed to sample Lower Aquifer wells require a capability of pumping from depths of 1,000 to 1,500 feet and require an initial expenditure (in 1980 dollars) in excess of $70,000, substantially more than the capital requirements for bailing. In addition, the time required for pump placement and withdrawal at these depths is about 7 to 12 hours, depending on the depth of the pump placement (i.e., sampling Upper or Lower Aquifer).

As pointed out above, a mobile pumping rig for sampling deep wells (i.e., Upper and Lower Aquifers) is very time-consuming and expensive, particularly on a frequent sampling basis. A more feasible approach may be a fixed pump in each well and a mobile generator for a power source. This approach requires substantially less manhours because the time for pump placement and withdrawal is eliminated. The approximate initial expenditure for a submersible pump in each well, capable of pumping from up to 1,600 feet at 40 gpm, is $6,600 to $7,800 (in 1980 dollars). Additional expenditures of $950 to $1,980 (in 1980 dollars) are required for each well for discharge pipe, power line, etc., depending on the depth of the pump.

To employ this sampling method efficiently, some expertise in the following areas is required: pump placement, discharge rate, duration of discharge, and representative sample collection. Although the submersible pump represents the most reliable method for collecting representative groundwater samples, incorrect procedures can produce inaccurate data. In addition, applying consistent procedures during each sampling event allows better comparison among the data collected on different dates.

Before establishing the sampling procedures for each well (i.e., pump placement, discharge rates, etc.), the wells need to be individually evaluated. Samples for water quality analysis should be collected only after the discharge has equilibrated. Additional factors to be considered during this evaluation include local hydrogeology, well construction, and well location, all of which can affect the time associated with obtaining a stable or equilibrated well discharge.

The importance of testing wells individually prior to establishing sampling protocols is apparent from the data presented in the following figures and tables. These data were collected from three wells installed by the USGS in the Piceance Basin. The typical well construction for these wells is shown in Figure 23.

The objective of this sampling program was to evaluate the variability of the water quality with pumping time. The types of data collected during this survey included continuous pH, temperature, and specific conductance measurements. Samples for detailed chemical analysis were also collected at selected intervals.

As Figures 30 through 34 indicate, the conductivity can vary substantially with pumping time. In the case of Well 75-1A (Figure 30), a very large and rapid change in conductivity was initially observed. After approximately one well volume, the conductivity stabilized and remained fairly constant for the duration of the test.

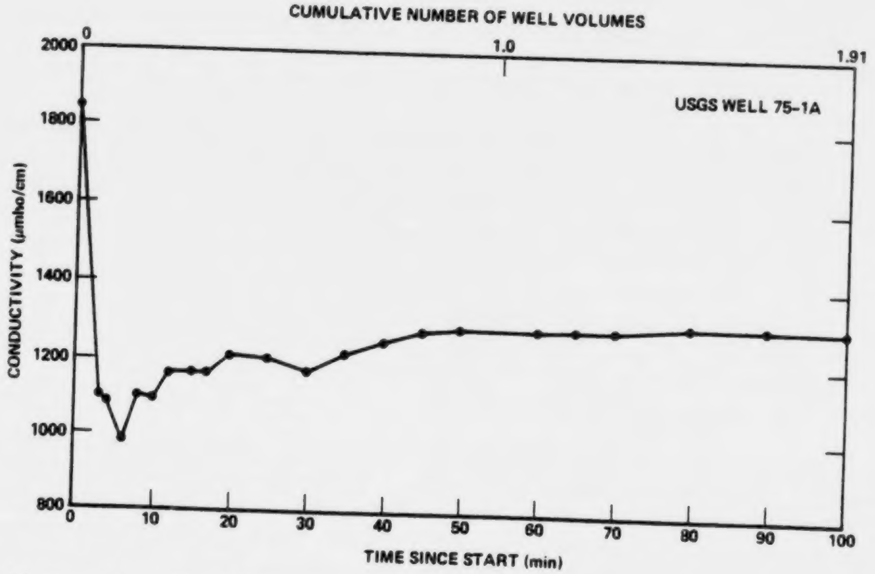


Figure 30. Variation in specific conductance with continued pumping, USGS Well 75-1A, 1980.

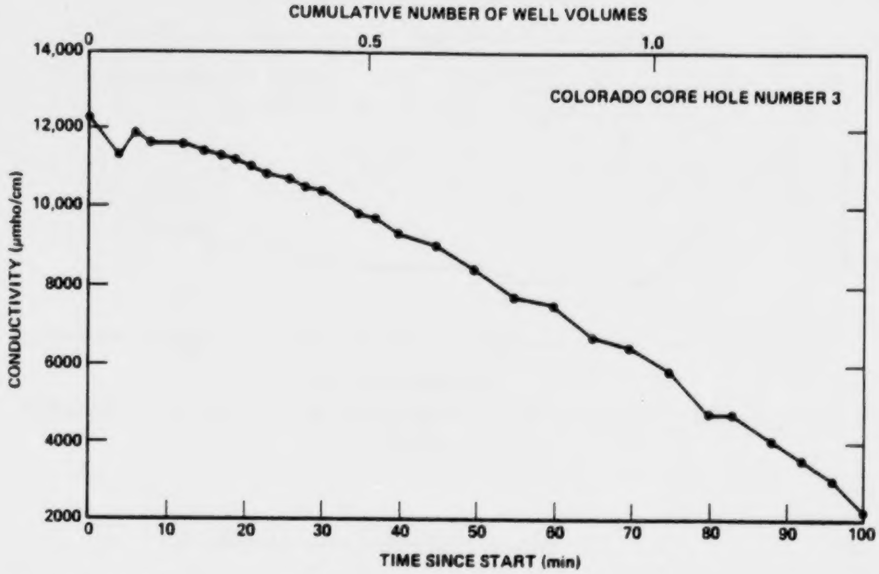


Figure 31. Variation in specific conductance with continued pumping, USGS Colorado Core Hole #3, 1980.

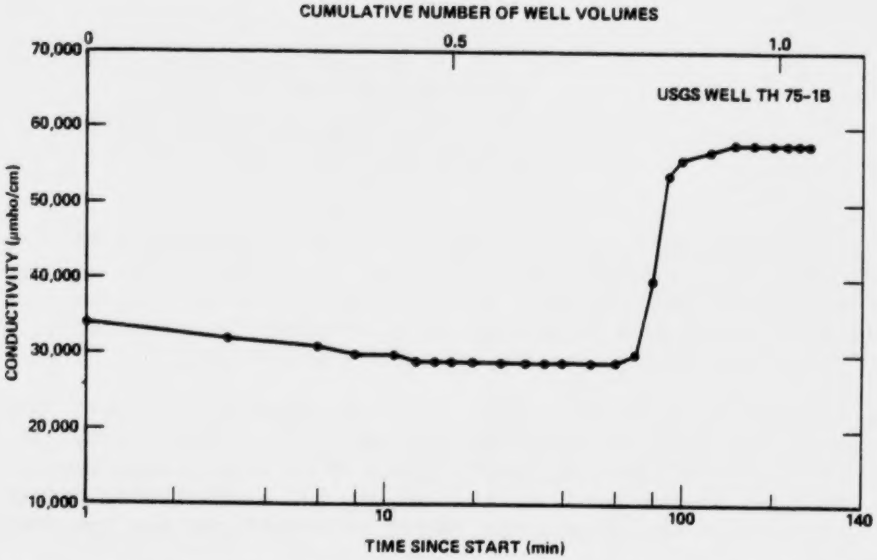


Figure 32. Variation in specific conductance with continued pumping, USGS Well TH75-1B, 1980.

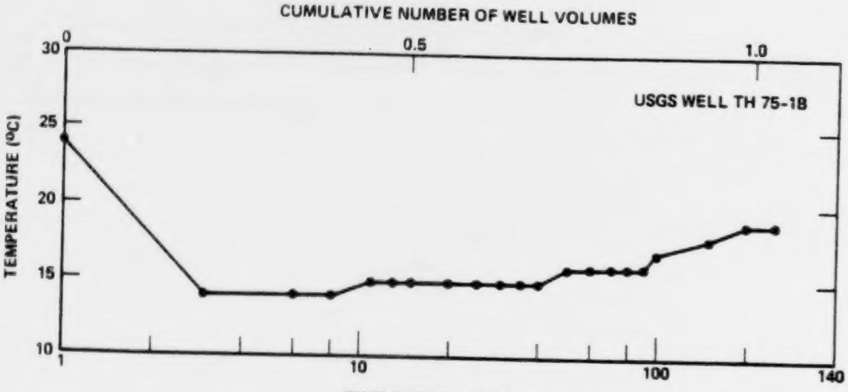


Figure 33. Variation of temperature of pumped discharge, Well TH75-1B, 1980.

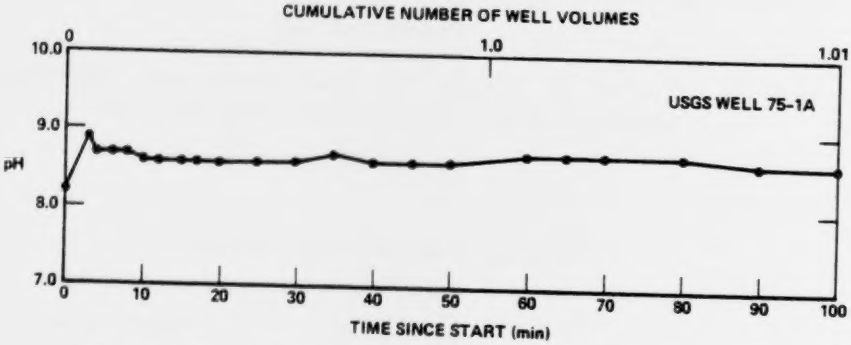


Figure 34. Variation in pH with continued pumping, USGS Well 75-1A, 1980.

The conductivity data collected for Colorado Core Hole #3 (Figure 31), steadily declined throughout the entire test. Conductivity values obtained toward the end of the test were about 20 percent of the initial measurements. Although more than one well volume was discharged from this well, the test was obviously not long enough for obtaining an equilibrated discharge.

An increasing trend in conductivity was observed for Well TH75-1B (Figure 32). During the test performed on this well, the conductivity was fairly stable at around 30,000 µmho/cm, until approximately three-quarters of a well volume had been discharged. At this point, the conductivity increased abruptly to around 58,000 µmho/cm, where it stabilized for the duration of the test.

The other constituents measured in the field also changed during the tests. The temperature of the discharge of Well TH75-1B (Figure 33) initially declined steadily and then appeared to increase slightly. The pH of Well

75-1A (Figure 34) initially increased one pH unit and stabilized after about 10 minutes of pumping.

These patterns of changes in the constituents measured in the field are also reflected in the water chemistry analysis (Table 15). For instance, the large change in conductivity for Well 75-1A is repeated for several major inorganic ions (potassium, sodium, bicarbonate, chloride, and sulfate), alkalinity, TDS, and fluoride concentrations. Most of the trace constituents (arsenic, boron, mercury, and selenium) were largely unchanged for the duration of the pumping.

The data collected during this survey and presented above point out the need for the individual testing of each well. It is obvious that a sample collected during the first few minutes of pumping and before conductivity has stabilized will not be representative. It is also obvious that the extraction of one well volume previous to representative sample collection is not a completely accurate rule-of-thumb, since the data for Colorado Core Hole #3 never stabilized, even after more than one and one-fourth volumes had been extracted.

In regard to pump location, it is recommended that the pump intake be placed approximately 5 feet above the open, perforated, or screened aquifer interval. The rationale for placing the pump in this location is as follows:

- A structurally unstable aquifer interval could fail due to the excessive stresses created by the pump if it were placed directly opposite the open, perforated, or screened interval

- If the well is not developed properly, the pump can produce sufficient turbulence in the aquifer interval to produce sand, etc.

- If the pump is placed in the aquifer interval and the discharge is too high, excessive drawdown may create cascading conditions that can produce sufficient turbulence to modify easily oxidized constituents

- Humenick et al. (1980) have pointed out that this pump location significantly reduces the volume of water necessary for extraction before representative aquifer water is obtained.

Figure 35 (from Humenick et al., 1980) illustrates two wells. Well A, with the pump intake 5 feet above the open aquifer interval, requires 12 gallons of discharge before formation water is produced. For Well B, the pump intake is 35 feet above the open interval and requires 77 gallons of discharge before representative formation water is produced.

In short, the following procedure defining sampling protocols is recommended for collecting representative samples from a well when using a submersible pump:

TABLE 15. WATER CHEMISTRY OF SAMPLES COLLECTED AFTER DISCHARGE OF VARYING WELL VOLUMES, USGS WELLS, PICEANCE BASIN, 1980

	Well volumes discharged							
	Well 75-1A			Core Hole # 3		Well TH75-1B		
Constituent[a]	0	1	2	0	1	0	0.2	1
Total dissolved solids	1,176	816	836	7,148	3,276	22,880	22,400	45,220
Calcium	4.3	13.8	11.7	1.8	3.2	3.6	2.0	1.5
Magnesium	32	54.9	52.5	24.6	29.3	4.4	2.2	2.8
Sodium	429	235	225	2,910	1,320	10,200	9,900	19,650
Potassium	1.2	0.4	0.4	21.3	13.6	22.5	22.1	32.5
Bicarbonate	944	695	708	3,496	1,719	23,300	23,640	48,560
Carbonate	<1	5	<1	39.5	14.1	32.5	<1	<1
Sulfate	184	149	144	229	228	131	87.2	61.7
Chloride	85.7	10.7	12.3	2,236	852	1,540	1,670	3,730
Fluoride	0.6	0.2	0.2	0.4	0.2	17.3	17.2	18.4
Ammonia	0.4	0.3	0.2	5.6	2.3	8.0	8.3	8.2
Arsenic	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.02	0.01
Boron	0.3	0.3	0.4	0.5	0.4	0.8	0.8	0.9
Mercury	<1	<1	<1	<1	<1	<1	<1	<1
Selenium	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01
Dissolved organic carbon	10.1	13.1	34.5	26.3	24.0	23.4	26.9	24.4

Note:

[a] Constituent units are mg/l except for pH units and specific conductance in µmhos/cm at 25°C.

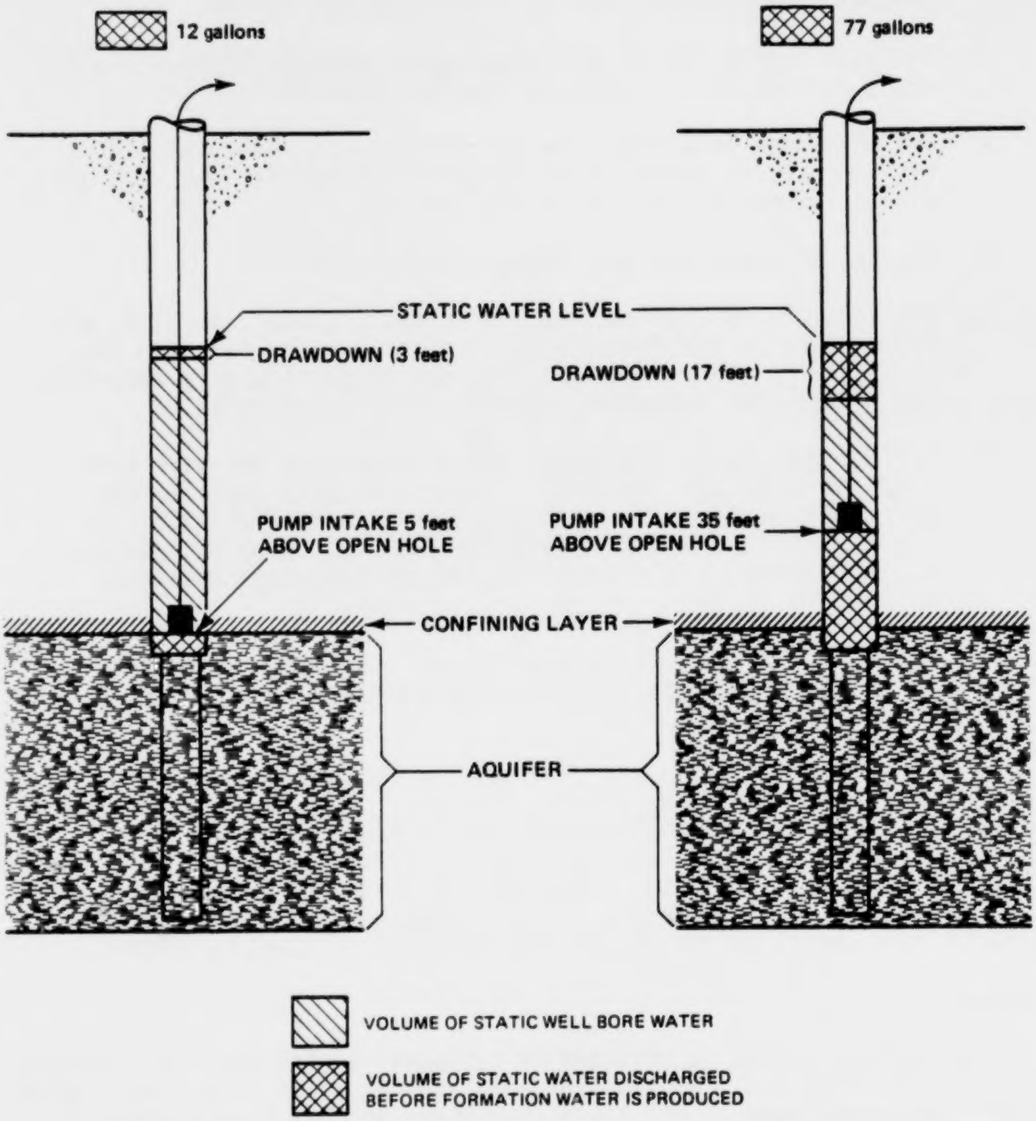

12 gallons
77 gallons
STATIC WATER LEVEL
DRAWDOWN (3 feet)
DRAWDOWN (17 feet)
PUMP INTAKE 5 feet ABOVE OPEN HOLE
PUMP INTAKE 35 feet ABOVE OPEN HOLE
CONFINING LAYER
AQUIFER
VOLUME OF STATIC WELL BORE WATER
VOLUME OF STATIC WATER DISCHARGED BEFORE FORMATION WATER IS PRODUCED

Figure 35. Comparison of pump locations and the volume of water necessary for extraction before representative aquifer water is obtained (modified from Humenick et al., 1980).

1. Compile well construction data, including well diameter, total depth, and perforated interval or aquifer interval in an open well.
2. Measure static water level and estimate well volume.
3. The pump intake should be placed approximately 5 feet above the open, perforated, or screened aquifer interval.
4. The discharge rate should be maintained at a moderately low rate to prevent excessive drawdown in the aquifer and well and minimize turbulent mixing in the annulus.
5. Extract at least one well volume from the well.
6. Continuously monitor and measure specific conductance, pH, and temperature in the field throughout the pumping period. Continuously monitoring these parameters is particularly important for little-used groundwater quality monitoring wells.
7. Collect the sample only after the field parameters have stabilized for a period of time. Although the data indicate that the conductivity is the most conclusive of aquifer water, it is suggested that all of the parameters be monitored to indicate representative aquifer water to prevent premature sample collection.
8. Collect the sample as close to the well head as possible to avoid potential contamination, precipitation of solutes, and the loss of dissolved gases.

It is recommended that these protocols be recharacterized periodically for each well, particularly for wells with large, open intervals. Once these protocols are defined or redefined and consistency among items such as discharge rate, time of collection, and pump placement is established, representative samples can be collected. However, to produce comparable data for establishing water quality trends, these procedures (i.e., pump placement, discharge rate, etc.) should be followed during each sampling effort.

Swabbing

The swabbing method is utilized by Cathedral Bluffs Shale Oil Company (operators of Tract C-b) for sampling deep aquifer wells. This methodology is a common procedure used in oil field operations and has been adapted for use on Tract C-b as a sampling procedure. The swabbing technique involves introducing a swabbing cup into the well, which is supported from the surface by a pipe, and removing a portion of the water from the 2-5/8-inch-diameter well. The water extracted from the well is discharged through a line to the place where the water quality samples are collected. This sampling method requires a capitalization cost (in 1980 dollars) of approximately $50,000 to $55,000 and requires four personnel for operation. Tract C-b contracts the equipment and personnel for each sampling effort, performed quarterly, at a cost of about $20,000.

The sampling approach applied by Tract C-b personnel is to completely evacuate a well volume of water. After this evacuation process has been performed, the well is allowed to recover for at least 24 hours. After this period, the swabbing equipment is returned to the site and the process is repeated and a sample is collected. Parameters measured in the field include specific conductance, pH, and temperature.

The advantages of swabbing are as follows:

- Swabbing can be used where the depth to water is relatively great and well diameters are relatively small
- At least one well volume can be obtained from the well, allowing for representative sample collection.

The disadvantages of this method include:

- Difficulty in regulating the volumes of water obtained from the well and the discharge rates
- Well contamination can occur when oil-field equipment is used for deep aquifer sampling; also, there is a potential for cross-contaminating the samples
- Very difficult to employ
- Accelerated plugging of the piezometer perforations is a potential problem, particularly with the small diameter of the piezometers
- Consistent water quality sample collection is difficult to achieve due to the vertical mixing of the well water upon extraction of the water; consistent swabbing depth during each sampling effort would help alleviate this problem.

In general, the use of swabbing is not recommended as a sampling technique.

SAMPLING FREQUENCY

Defining an appropriate sampling frequency is a complex issue influenced by location of sampling sites, monitoring goals, climatological factors, and characteristics of groundwater flow. As a result, sampling frequency should be defined on a case-by-case and likely trial-and-error basis. One of the key factors is groundwater flow rate. If flow from a potential pollution source to a monitoring well is expected to be on the order of decades (assuming a release occurs), then very frequent sampling does not seem warranted and perhaps annual sampling for a few indicator constituents would suffice.

The complexity of the hydrogeology of the oil shale region makes estimation of groundwater flow rate difficult at best and the actual flow rates highly site specific. Table 16 lists some estimates of travel time in the Upper Aquifer zone of the Piceance Creek Basin. The wide variation in results reinforces the care needed in design of monitoring programs, as our understanding of the system is incomplete.

TABLE 16. FLOW RATES OF THE UPPER AQUIFER, PICEANCE CREEK BASIN, ESTIMATED BY THREE STUDIES

Study reference	Flow velocity (feet per day)	Travel time (years to travel 1 mile)
Lawrence Berkeley Labs, 1978 (data from Weeks et al., 1974)	0.05	300
U.S. Atomic Energy Commission, 1972	0.36 - 0.78[a]	20 - 40
Knutson, 1973	11.7	1.2

Note:

[a] Range for representative gradient and maximum gradient cases.

SAMPLE HANDLING AND PRESERVATION

Proper methods of sample handling and preservation should be exercised to minimize the changes in the geochemical environment from which the sample is extracted. The chemical qualities of some samples can change within a few hours or minutes following withdrawal. Other constituents can be preserved and stabilized for a limited period of time, whereas still other constituents have a shelf life of up to 6 months. In addition to sample time constraints, the sampler should be aware of potential problems that may arise from improper selection of sample volumes, containers, and preservatives, as well as inadequate field records and chain-of-custody preparations.

Field Data Collection

Parameters that should be measured in the field include pH, temperature, and specific conductance. If dissolved oxygen and oxidation-reduction potential measurements are required, these should also be determined in the field. Although some of these parameters have holding times of up to 24 hours (see Table 17), it is recommended that these determinations be made in the field with the appropriate apparatus to prevent inaccurate results from delay in receipt of the samples at the analytical laboratory. In addition to holding times Table 17, derived from U.S. EPA (1974), contains information regarding the recommended choice of preservatives and sample containers and volume requirements for various constituents.

TABLE 17. RECOMMENDATION FOR SAMPLING AND PRESERVATION OF SAMPLES ACCORDING TO MEASUREMENT[a]

Parameter Measured	Volume Required (ml)	Container[b]	Preservative	Holding Time[c]
Acidity	100	P,G	None required	24 hours
Alkalinity	100	P,G	Cool, 4°C	24 hours
Arsenic	100	P,G	HNO_3 to pH < 2	6 months[d]
BOD	1,000	P,G	Cool, 4°C	6 hours
Bromide	100	P,G	Cool, 4°C	24 hours
Chloride	50	P,G	None required	7 days
Chlorine	200	P,G	Determine on site	No holding
COD	50	P,G	H_2SO_4 to pH < 2	7 days
Color	50	P,G	Cool, 4°C	24 hours
Cyanides	500	P,G	Cool, 4°; NaOH to pH 12	24 hours
Dissolved Oxygen				
Probe	300	G only	Determine on site	None
Winkler	300	G only	Fix on site	4 to 8 hours
Fluoride	300	P,G	None required	7 days
Hardness	100	P,G	Cool, 4°C; HNO_3 to pH < 2	6 months[d]
Iodide	100	P,G	Cool, 4°C	24 hours
MBAS	250	P,G	Cool, 4°C	24 hours
Metals				
Dissolved	200	P,G	Filter on site; HNO_3 to pH < 2	6 months[d]
Suspended	200		Filter on site	6 months
Total	100	P,G	HNO_3 to pH < 2	6 months[d]
Mercury				
Dissolved	100	P,G	Filter; HNO_3 to pH < 2	38 days (glass); 13 days (hard plastic)
Total	100	P,G	HNO_3 to pH < 2	38 days (glass); 13 days (hard plastic)[d]
Nitrogen				
Ammonia	400	P,G	Cool, 4°C; H_2SO_4 to pH < 2	24 hours
Kjeldahl, total	500	P,G	Cool, 4°C; H_2SO_4 to pH < 2	24 hours[e]
Nitrate	100	P,G	Cool, 4°	24 hours
Nitrite	50	P,G	Cool, 4°C	48 hours
NTA	50	P,G	Cool, 4°C	24 hours
Oil and grease	1,000	G only	Cool, 4°C; HCl or H_2SO_4 to pH < 2	24 hours
Organic carbon	25	P,G	Cool, 4°C; HCl or H_2SO_4 to pH < 2	24 hours
pH	25	P,G	Determine on site	6 hours

(continued)

TABLE 17 (continued)

Constituent	Volume Required (ml)	Container[b]	Preservative	Holding Time[c]
Phenolics	500	G only	Cool, 4°C; H_3PO_4 to pH < 4; 1.0 g $CuSO_4$/l	24 hours
Phosphorus				
Orthophosphate, dissolved	50	P,G	Filter on site; cool 4°C	24 hours
Hydrolyzable	50	P,G	Cool, 4°C; H_2SO_4 to pH < 2	24 hours[e]
Total	50	P,G	Cool, 4°C; H_2SO_4 to pH < 2	24 hours[e]
Total, dissolved	50	P,G	Filter on site; cool, 4°C H_2SO_4 to pH < 2	24 hours[e]
Residue				
Filterable	100	P,G	Cool, 4°C	7 days
Nonfilterable	100	P,G	Cool, 4°C	7 days
Total	100	P,G	Cool, 4°C	7 days
Volatile	100	P,G	Cool, 4°C	7 days
Settleable matter	1,000	P,G	None required	24 hours
Silica	50	P only	Cool, 4°C	7 days
Specific conductance	100	P,G	Cool, 4°C	24 hours[f]
Sulfate	50	P,G	Cool, 4°C	7 days
Sulfide	50	P,G	2 ml zinc acetate	24 hours
Sulfite	50	P,G	Determine on site	No holding
Temperature	1,000	P,G	Determine on site	No holding
Turbidity	100	P,G	Cool, 4°C	7 days

Notes:

[a] More specific instructions for preservation and sampling are found with each procedure as detailed in U.S. EPA (1974). A general discussion on sampling water and industrial wastewater may be found in ASTM, Part 31, p. 72-82 (1976), Method D-3370.

[b] Plastic (P) or glass(G); for metals polyethylene with a polypropylene cap (no liner) is preferred.

[c] It should be pointed out that holding times listed above are recommended for properly preserved samples based on currently available data. It is recognized that for some sample types, extension of these times may be possible, while for other types, these times may be too long. Where shipping regulations prevent the use of the proper preservation technique or the holding time is exceeded, such as the case of a 24-hour composite, the final reported data for these samples should indicate the specific variance.

[d] Where HNO_3 cannot be used because of shipping restrictions, the sample may be initially preserved by icing and immediately shipped to the laboratory. Upon receipt in the laboratory, the sample must be acidified to a pH < 2 with HNO_3 (normally 3 ml 1:1 HNO_3/l is sufficient). At the time of analysis, the sample container should be thoroughly rinsed with 1:1 HNO_3 and the washings added to the sample (volume correction may be required).

[e] Data obtained from National Enforcement Investigations Center, Denver, Colorado, support a 4-week holding time for this parameter in sewerage systems (SIC 4952).

[f] If the sample is stabilized by cooling, it should be warmed to 25°C for reading, or temperature correction made and results reported at 25°C.

Today, field studies are supported by some fairly precise, portable, analytical equipment that furnish accurate data, thus eliminating any effects delayed sample shipment may have on the validity of water chemistry analysis performed at the laboratory. Furthermore, these determinations can be easily measured and provide valuable on-site information regarding aquifer characteristics of aid in the collection of representative aquifer water.

Specific Conductance--

Specific conductance is a measure of the ability of a solution to transmit an electrical current. In water samples, the specific conductance is an indication of the concentration of dissolved solids (i.e., salinity). The unit of measurement for specific conductance is the inverse of the resistivity and is typically expressed in micromhos per centimeter.

Specific conductance is an important measurement that should always be made in the field during sample collection. This parameter is very useful in determining when aquifer water has been obtained and thereby aids in the collection of representative samples. The recommended holding time is only 24 hours (U.S. EPA, 1979), which may present problems in obtaining accurate results from the analytical laboratory if sample shipment is delayed.

Temperature--

Temperature should always be measured immediately after sample withdrawal. It is a very easy measurement to obtain, and the equipment used for its determination should be accurate to within ±0.1°C to allow for future geochemical evaluations of equilibrium thermodynamics. Also, field determinations of aquifer water temperatures prevent inaccurate measurements due to the modification of the sample temperature during sample preservation and transportation.

pH--

Wood (1976) provides the following description for pH: "The pH of a solution is a measure of effective hydrogen-ion concentration or, more accurately, it is the negative logarithm of the hydrogen-ion activity in moles per litre: $\mathrm{pH} = -\log (\mathrm{H}^+)$." The pH of an aqueous solution is typically controlled by the disassociation of acids, bases, and hydrolysis. The pH of a groundwater sample is further controlled by the carbonate system, including dissolved carbon dioxide, bicarbonate, and carbonate ions.

The pH of an aqueous solution can be measured precisely and quickly with mechanical instruments. Some researchers have found that pH is the best parameter for determining that representative aquifer water has been obtained from a well (Brown et al., 1970; Wood, 1976; and Humenick et al., 1980). The holding time for pH is 7 hours (U.S. EPA, 1979), however, which can affect analytical determinations if sample shipment is delayed. Therefore, it is highly recommended that pH be measured in the field at the time of sample withdrawal.

Dissolved Oxygen and Oxidation-Reduction Potential--

Geochemical evaluations of a groundwater system may require dissolved oxygen and oxidation-reduction potential measurements. If this is the case, these measurements should be conducted in the field at the time of sample collection for accurate results. Particular care must be exercised during these measurements to prevent atmospheric aeration of the sample during collection and analysis. Many companies produce precise, portable, easily used, analytical equipment for these measurements.

Field Notes and Records, Sample Labels

The following notes and records for sample collection should be maintained for future data evaluation:

- Time and date of arrival, sample collection, and departure from the well site
- The water level of the well
- Description of the sample source, including well number and location and the following additional information (if applicable):
  - -- Depth of sample collection (of critical importance for bailing)
  - -- Duration of pumping previous to sample collection
  - -- Well volumes extracted previous to sample collection
  - -- Pump placement
- Well data information pertaining to well construction and completion and the aquifer(s) or section of aquifer in which the well is completed, including:
  - -- Length and depth to screened interval, open interval, and/or casing interval
  - -- Well annulus
  - -- Total depth of well
- Water quality data for specific conductance, pH, temperature, water level, etc.
- Sampling specifications, particularly the procedures previously employed for sample collection, that will establish consistent sampling methods for each sampling effort, including:
  - -- Pump placement

  - Discharge rate
  - Time of sample collection, etc.
- The type of sampling methodology utilized for sample withdrawal
- Field observations pertinent to sample collection, including color, sediment, turbidity, etc.
- The reason for the sampling effort
- The results of field determinations performed at the time of sample collection (e.g., temperature, specific conductance, pH, oxidation-reduction potential, dissolved oxygen, etc.)
- Any problems encountered in the field during sample collection.
- The identity of the sample collector.

Sample labels should be prepared before the sampling effort and affixed to the sample container. If possible, the information should be duplicated on the sample container itself to prevent errors resulting from label detachment during sample handling and shipment. In addition, waterproof pens should be used by the sampler to prevent dissipation. The following information should be included on the sample label and container:

- Time and date of sample collection (if multiple samples are to be collected from the same well, the hierarchy or succession of the samples collected should also be noted)
- The well number and location
- The preservative (if any) utilized
- If the sample has been filtered in the field or been sent to the analytical laboratory unfiltered.

Field Handling and Preservation Techniques

Preservation of samples through the use of techniques currently available and easily applied in the field can only retard the chemical or biological changes that take place after the sample has been withdrawn from the well. Methods of preservation are relatively limited and are intended to: (1) retard biological activity, (2) retard hydrolysis of chemical compounds and complexes, (3) reduce volatility of constituents, and (4) reduce absorption effects (U.S. EPA, 1979). In general, preservation techniques include pH control, chemical addition, refrigeration, and freezing. The following preservatives are used to retard sample changes after collection (U.S. EPA, 1977):

Preservative	Action	Applicable To
$HgCl_2$	Bacterial inhibitor	Nitrogen forms, phosphorus forms
Acid (HNO_3)	Metals solvent, prevents precipitation	Metals
Acid (H_2SO_4)	Bacterial inhibitor	Organic samples (COD, oil and grease, organic carbon)
Acid (H_2SO_4)	Salt formation with organic bases	Ammonia, amines
Alkali (NaOH)	Salt formation with volatile compounds	Cyanides, organic acids
Refrigeration	Bacterial inhibitor	Acidity-alkalinity, organic materials, BOD, color, odor, organic P, organic N, carbon, etc., biological organisms (coliform, etc.)

Containers used for sample collection should be selected for their nonreactivity with the particular analytical parameter to be measured. Depending on the constituent(s), the containers typically consist of either glass or plastic. Table 17 provides the recommended sample container for the particular analysis of interest. In addition, it is generally advantageous to prepare the sample containers with the appropriate preservative prior to sample collection. This procedure may be very time-consuming since separate bottles and chemical preservatives are required for certain parameters, which may result in several containers for each sample collected. However, this preparation will result in the elimination of laborious effort in the field during sample collection.

Determination of dissolved concentrations will require the sample to be filtered through a 0.45-micron filter prior to acidification. If the sample is not filtered and acid is added as a preservative, much of the particulate matter will be dissolved by the acid resulting in anomalously high concentrations of dissolved constituents. It is also recommended that the sample be filtered as soon as possible after withdrawal, preferably in the field. However, samples to be used for on-site temperature, dissolved oxygen, pH, and/or oxidation-reduction potential measurements should not be filtered before these determinations have been made.

After the sample has been filtered and preserved, the recommended procedure is to place the samples on ice for further preservation during shipment. The use of an ice chest is the preferred approach for sample shipment since ice chests are easy to handle and are insulated such that a temperature between 0° and 10°C can be maintained for a limited period of time.

Sample Shipment

The relative remoteness of the oil shale region can result in some delay in receipt of the groundwater quality samples at commercial analytical laboratories. To evaluate the effects of this potential problem on the results of chemical analysis, a testing program was initiated by Tempo. The program was conducted in conjunction with Cathedral Bluffs Shale Oil Company personnel on Federal Lease Tract C-b. The field effort involved the sampling of three alluvial wells with a portable, submersible pump. At each well, the samples were collected after the field parameters (i.e., specific conductance, pH, and temperature) had stabilized. The sample collected from each well was handled as follows:

- The sample was split three ways and preserved with EPA-recommended preservatives (see Table 17)
- Samples were refrigerated or cooled as recommended by EPA (see Table 17)
- The samples were then shipped to the analytical laboratory for analysis in the following sequence:
  - -- First sample split was analyzed within 24 hours of sample collection
  - -- Second sample split was analyzed 7 days after sample collection
  - -- Third sample split was analyzed 15 days after sample collection.

This sequence of sample analysis was intended to simulate circumstances that can arise during field sampling efforts. The initial split represents the optimum situation for sample shipment, i.e., immediately after sample collection. The second sample split represents the situation where samples collected during the week are shipped to the laboratory for analysis at the end of the week. The third sample split represents either a lengthy field survey resulting in a shipment of samples at the end of two working weeks or a significant delay in the receipt of the samples at the laboratory due to shipping problems.

The chemical analyses presented in Tables 18 through 20 represent samples collected from alluvial wells A-6, A-9, and A-12, respectively. The constituents of the chemical analyses consisted of specific conductance, pH, total dissolved solids (TDS), bicarbonate, carbonate, chloride, ammonia, sulfate, nitrate, and dissolved organic carbon (DOC). The constituents chosen were based on the following EPA holding-time recommendations:

TABLE 18. CHEMICAL ANALYSIS OF SAMPLES TAKEN FROM ALLUVIAL WELL A-6 FOR THREE DIFFERENT TIMES OF ANALYSIS

	Within 24 hours					7 days					15 days				
Constituent	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.
Specific Conductance[a]	1,270	1,260	1,280	1,270	8.2	1,220	1,210	1,205	1,212	6.2	1,250	1,260	1,255	1,255	4.1
pH[b]	7.8	7.75	7.8	7.8	0.02	7.70	7.80	7.70	7.73	0.05	7.70	7.80	7.79	7.76	0.05
Bicarbonate	712	706	710	709	2.5	706	702	699	702	2.9	693	699	699	697	2.8
Carbonate	<1	<1	<1	<1	0	<1	<1	<1	<1	0	<1	<1	<1	<1	0
Sulfate	189	208	195	197	7.9	249	233	243	242	6.6	234	242	240	239	3.4
Chloride	16.2	15.8	15.8	15.9	0.2	12.4	12.9	12.8	12.7	0.22	12.8	12.6	12.9	12.9	0.1
TDS	888	880	884	884	3.3	918	912	920	917	3.4	928	920	920	923	3.8
Ammonia	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	0
Nitrate	0.20	0.20	0.20	0.20	0	0.20	0.20	0.30	0.23	0.5	0.20	0.20	0.20	0.20	0
Fluoride	0.33	0.34	0.33	0.33	0	0.40	0.40	0.41	0.40	0	0.39	0.40	0.40	0.40	0
DOC	16	14	14	15	1	46	52	49	49	2.4	63	61	56	60	2.9

Notes:

[a] Measured 1,350 in the field, units µmhos/cm at 25°C..

[b] Measured 7.5 in the field, pH units.

Repl -- Replicate Sampling; Std. Dev. -- Standard Deviation. Constituent units mg/l.

TABLE 19. CHEMICAL ANALYSIS OF SAMPLES TAKEN FROM ALLUVIAL WELL A-9 FOR THREE DIFFERENT TIMES OF ANALYSIS

	Within 24 hours					7 days					15 days				
Constituent	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.
Specific Conductance[a]	1,110	1,100	1,095	1,102	6.2	1,050	1,055	1,055	1,053	2.4	1,085	1,110	1,115	1,103	13.1
pH[b]	7.97	7.99	7.85	7.94	0.06	7.93	7.90	7.82	7.88	0.05	8.05	8.05	7.98	8.03	0.04
Bicarbonate	482	486	486	485	1.9	489	493	492	491	1.7	492	489	492	491	1.4
Carbonate	<1	<1	<1	<1	0	<1	<1	<1	<1	0	<1	<1	<1	<1	0
Sulfate	299	296	305	300	3.7	315	322	320	319	2.9	355	325	329	330	4.1
Chloride	7.22	7.59	7.6	7.47	0.26	4.90	5.32	5.30	5.17	0.19	5.20	5.65	5.26	5.37	0.17
TDS	784	784	776	781	3.8	796	800	804	800	3.3	812	804	816	811	5.0
Ammonia	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	0
Nitrate	1.0	0.9	1.0	0.97	0.04	1.0	0.9	1.0	0.97	0.04	1.0	0.9	1.0	0.97	0.04
Fluoride	0.20	0.18	0.19	0.19	0	0.19	0.21	0.20	0.20	0	0.19	0.20	0.20	0.20	0
DOC	8	7	10	8	1.3	34	42	37	38	3.3	45	51	50	49	2.6

Notes:

[a] Specific conductance measured 1,170 in the field, units µmhos/cm at 25°C.

[b] pH measured 7.6 in the field, pH units.

Repl -- Replicate Sampling; Std. Dev. -- Standard Deviation. Constituent units mg/l.

TABLE 20. CHEMICAL ANALYSIS OF SAMPLES TAKEN FROM ALLUVIAL WELL A-12 FOR THREE DIFFERENT TIMES OF ANALYSIS

	Within 24 hours					7 days					15 days				
Constituent	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.	Repl 1	Repl 2	Repl 3	Mean	Std. Dev.
Specific Conductance[a]	1,410	1,400	1,400	1,403	4.7	1,385	1,390	1,375	1,380	4.1	1,405	1,395	1,400	1,400	4.1
pH[b]	7.8	7.85	7.8	7.82	0.02	7.81	7.86	7.85	7.84	0.02	7.83	7.84	7.85	7.84	0
Bicarbonate	598	596	596	597	1.0	596	606	602	601	4.1	609	596	602	602	5.3
Carbonate	<1	<1	<1	<1	0	<1	<1	<1	<1	0	<1	<1	<1	<1	0
Sulfate	398	418	402	406	8.6	469	447	450	455	9.7	472	465	451	462	8.9
Chloride	9.71	10.10	9.31	9.71	0.32	7.22	7.31	8.17	7.57	0.43	7.56	7.56	7.47	7.53	0.04
TDS	1,052	1,040	1,056	1,049	6.8	1,116	1,116	1,100	1,111	7.5	1,136	1,156	1,056	1,116	43.2
Ammonia	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	0
Nitrate	0.30	0.20	0.20	0.23	0.05	0.20	0.20	0.30	0.23	0.05	0.20	0.20	0.20	0.20	0
Fluoride	0.20	0.18	0.18	0.19	0.01	0.23	0.20	0.19	0.21	0.02	0.20	0.20	0.20	0.20	0
DOC	15	15	19	16	1.9	37	35	34	35	1.3	57	56	55	56	0.8

Notes:

[a] Specific conductance measured 1,350 in the field, units µmhos/cm at 25°C.

[b] pH measured 7.5 in the field, pH units.

Repl -- Replicate Sampling; Std. Dev. -- Standard Deviation. Constituent units mg/l.

Constituent	EPA Recommended Holding Time
Specific conductance	24 hours
pH	6 hours
Total dissolved solids	6 months
Bicarbonate	24 hours
Carbonate	24 hours
Chloride	7 days
Fluoride	7 days
Ammonia	24 hours
Nitrate	24 hours
Sulfate	7 days
Dissolved organic carbon	24 hours
Trace metals	6 months

Due to the long shelf life of the trace metals (i.e., 6 months), these constituents were not incorporated in the chemical analysis.

The constituents that display changes in concentration during the holding periods are specific conductance, pH, sulfate, chloride, and DOC. TDS concentrations also vary somewhat between holding periods. The other constituents either had concentrations below detection limits (e.g., ammonia and carbonate) or maintained fairly uniform concentrations throughout the entire 15-day period (e.g., bicarbonate, nitrate, and fluoride).

In every sample, the specific conductance and pH data differ somewhat between the field and the analyses performed after 24 hours. After this period, the next two analyses indicate that the pH remains fairly constant. The specific conductance does vary slightly during the latter two analyses. The TDS data do not reflect the trend observed for specific conductance but instead generally increase slightly during the 15-day period.

The sulfate and chloride concentrations were also variable, particularly between the 24-hour analysis and the 7-day analysis. In general, sulfate increased in concentration during the holding periods, whereas the chloride concentration decreased during the same interim. In some instances, such as the decrease in chloride concentration during the initial 7-day period for the sample collected from Well A-6, the changes were considerable.

The constituent that displayed the most appreciable variability was DOC. In all three well samples, the DOC concentration increased significantly over the 15-day period. However, the polyethylene sample containers may have contributed somewhat to this trend. It has been demonstrated that polyethylene can contribute contaminating organics to the sample and affect the DOC concentrations.

Summers (1972) has demonstrated that changes in pH, specific conductivity, and the carbonate-bicarbonate system are all indicative of sample aging. Typically, the following reaction will control these changes: $CaCO_3 + H_2O + CO_2 \rightarrow Ca_2^{+} + 2HCO_3^{-}$. Changes in the CO2 concentration can also influence these constituents. The data collected by this survey do not reflect appreciable increases in the bicarbonate concentration during the 15-day period. However, in that the greatest increase in pH occurred during the first 24 hours, perhaps the samples achieved equilibrium before the first analysis by the laboratory. If such were the case, a significant increase in the bicarbonate would require immediate analysis for detection and probably could not be observed after a period of time, in this case 24 hours.

The data also indicate that chloride and sulfate may be the most sensitive parameters with respect to sample holding-time considerations. Although the EPA-recommended holding time for these constituents is 7 days, it is apparent from the data that the most significant changes in the concentrations of these constituents occurred during the first 7 days. Due to the potential contamination of the DOC by the polyethylene sample container, the effects of the holding times on this constituent are inconclusive.

It is apparent that correct and quick sample shipment is critical for accurate analytical results. In the oil shale regions, time constraints may prevent field personnel from delivering the samples to the laboratory, particularly if the sampling effort extends beyond 24 hours. In this case, the most efficient procedure is to ship the samples via commercial bus or plane. This procedure is very inexpensive (on the order of $2 to $10 per ice chest) and will eliminate unnecessary trips to the analytical laboratory by field personnel. Furthermore, transportation by these methods is very reliable and provides reasonable assurance against changes in sample chemistry due to prolonged sample storage.

Chain of Custody

The typical chain of custody in the oil shale region includes the sampler, the individuals involved in the transportation, and the individuals handling the sample at the analytical laboratory. The proper procedures that should be followed during this chain of custody are:

- Include as few people as possible in the chain of custody.
- Collect, preserve, and ice the samples according to the recommended procedures
- Label each sample container according to the recommendations previously presented indicating the analysis required on the sample labels if preparations have not previously been made
- Maintain a field notebook or logbook during each survey and store it in a safe place, with all entries signed by the individual responsible for the field effort

- Assign complete responsibility for the collected samples (including those delivered by field personnel) to the individual conducting the effort, including overseeing all transportation activities (including timely delivery of the samples to the busline or airline facility and their receipt at the analytical laboratory) and maintaining a record of these activities as follows: time and date of deliveries, method of transportation, and the individual(s) performing the transportation.

Furthermore, effort should be made to have the laboratory performing the chemical analysis retain a custodian to maintain a record indicating:

- Time and date of sample receipt
- The person receiving the sample
- The sample number
- The number assigned to each sample by the laboratory.

This custodian should provide for proper handling and storage of the samples prior to analysis. In addition, the custodian should be responsible for distribution of the samples to the individual performing the analysis, recording the individual's identity, and assuring that immediate analysis is conducted to avoid water chemistry changes due to prolonged sample storage.

SELECTION OF CONSTITUENTS FOR MONITORING

The proper location of monitoring points is largely determined by the locale and character of the potential sources of groundwater quality impact and the local source hydrogeology. The constituents for monitoring are selected so as to provide a cost-effective indication of the nature and extent of impact on groundwater quality. Assessment of enrichment factors (or concentration change above ambient), specific indicator constituents, and stable isotopes are possible approaches for selection of constituents for chemical analysis.

Enrichment Factors

In this subsection, enrichment factors, EF, will be calculated for major possible sources of groundwater impact according to the expression:

$$EF = \frac{\text{concentration from potential pollution source}}{\text{concentration in aquifer}} .$$

For this assessment, representative baseline water quality levels were selected (Table 21). Concentrations from the more saline sections of the Lower Aquifer are included principally in Table 21 in order to most clearly demarcate the differences in enrichment factors. Representative concentrations of constituents in retort water and in spent shale leachate were used in this preliminary analysis.

TABLE 21. REPRESENTATIVE CONCENTRATIONS IN GROUNDWATERS ADAPTED FOR THIS STUDY

	Springs, seeps and alluvial aquifer	Upper Aquifer	Saline Lower Aquifer	Lower working limit of detection, Denver Laboratory[a]
Gross Parameters (mg/l)				
Conductance (μmho/cm)	1,300	1,500	7,000	2
pH	6 - 8	7 - 8.5	8	---
TDS	900	1,000	6,000	1
Ammonia	0.4	0.5	10	100
Bicarbonate	500	500	4,000	5
Calcium	70	50	200	0.05
Carbonate	3	3	20	5
Chloride	10	10	20	0.2 - 1
Cyanide	0.01	0.01	0.01	0.002
Magnesium	70	70	20	50
Nitrate	2	1.0	0.5	0.02
Potassium	2	2	20	0.1
Silica	20	20	10	1
Sodium	150	200	2,500	0.1
Strontium	2	2	---	0.01
Sulfate	350	350	60	3 - 10
Phosphate	< 0.1	< 0.1	< 0.1	0.1
Kjeldahl nitrogen	2	---	---	0.1
Nitrite	0.2	---	---	0.02
Sulfide	0.2	0.6	0.6	0.1
Minor and Trace Elements (μg/l)				
Aluminum	300	200	250	100
Arsenic	5	10	10	2 - 50
Barium	50	100	800	50
Beryllium	<100	<10	---	5
Boron	500	1,000	40,000	50
Bromine	20	50	500	2,000

(continued)

TABLE 21 (continued)

	Springs, seeps and alluvial aquifer	Upper Aquifer	Saline Lower Aquifer	Lower working limit of detection, Denver Laboratory[a]
Minor and Trace Elements (μg/l) (continued)				
Cadmium	17	10	5	2
Chromium	11	2 - 300	10	5 - 10
Cobalt	8	3	5	10
Copper	30	70	70	10
Fluoride	400	7,000	20,000	100
Iron	500	500 - 5,000	800	10
Lead	50	10 - 100	100	1 - 10
Manganese	30 - 500	100	100	5
Mercury	0.4 - 3	0.4 - 3	0.4 - 2	0.02
Molybdenum	40	50	50	5
Nickel	30	20	10	10
Radiation, alpha (pCi/l)	5	5	20	---
Radiation, beta (pCi/l)	4	4	20	---
Rubidium	10	20	70	---
Scandium	4	---	---	---
Selenium	<10	<10	<10	5
Silver	<1	10	10	0.05 - 10
Thallium	---	---	---	5 - 50
Titanium	200	100	100	300
Uranium	---	<30	<20	---
Vanadium	5	2	16	5
Zinc	200	200	200	5
Lithium	<100	---	---	5
Gross Organic Parameters				
TOC (mg/l)	5	3	10	1
Phenol (μg/l)	3	3	1 - 10	1
DOC (mg/l)	5	8	20	---
COD (mg/l)	16	18	13	10

Note:

[a] Using standard methods.

Also shown in Table 21 are the lowest concentrations typically reported by a Denver water quality laboratory employing standard methods. As can be seen, the average concentrations of P, V, Ti, As, Se, Ni, Co, Cu, Cd, Br, Be, Ba, and As are close to or below these lower limits. It is therefore likely that many of these trace element species were determined by spark source mass spectroscopy which resulted in the improvement in detectability. This, however, resulted in a degradation in precision in comparison to standard methods.

Table 22, which lists enrichment factors for the Lower Aquifer, is pertinent to the contamination of the Upper Aquifer, springs, and seeps by the Lower Aquifer. As can be seen, NH_4, K, Na, B, and Br are enriched at least 10 times in the Lower Aquifer compared to either the Upper Aquifer or spring waters. In addition, Ba and F are enriched in the Lower Aquifer compared to spring waters. It is likely, therefore, that these species would be indicators of intrusion of waters from the Lower Aquifer.

TABLE 22. SPECIES ENRICHED IN THE LOWER AQUIFER

	Enrichment factors	
	$\frac{\text{Lower Aquifer}}{\text{Upper Aquifer}}$	$\frac{\text{Lower Aquifer}}{\text{Springs and seeps}}$
Conductance	4.6	5.4
TDS	6	6.6
Ammonia	20	25
Bicarbonate	8	8
Calcium	4	4
Potassium	10	10
Sodium	13	17
Barium	8	16
Boron	40	80
Bromine	10	25
Fluoride	2.9	50
Phenolics	0.3 - 10	0.3 - 10

Table 23 lists enrichment factors for leachates and shows that the parameters pH, TDS, Cl, Na, SO_4, Mo, Se, and TOC are likely indicators (i.e., tracers) of contamination in the Lower Aquifer. Although carbonate appears to be enriched in leachate, this reflects an increase in pH rather than an increase in total $HCO_3 + CO_3$.

TABLE 23. ENRICHMENT FACTORS ESTIMATED FOR SPENT MIS OIL SHALE LEACHATE

	Enrichment factors	
	Leachate	Leachate
	Upper Aquifer	Lower Aquifer
Gross Parameters (mg/l)		
Conductance (umhos/cm)	2.5 - 52	0.54 - 11
pH	0.6 - 2	0.6 - 1.5
TDS	6 - 140	1 - 23
Bicarbonate	0.2 - 0.4	---
Calcium	0.2 - 60	0.05 - 16
Carbonate	330 - 1,000	50 - 150
Chloride	6.4 - 310	3.2 - 160
Cyanide	---	---
Magnesium	0.01 - 67	0.05 - 235
Nitrate	---	---
Potassium	2.5 - 70	0.25 - 7
Silica	0.5 - 1.0	1.0 - 2.0
Sodium	0.37 - 180	0.03 - 14
Strontium	---	---
Sulfate	0.51 - 260	3 - 1,500
Kjeldahl nitrogen	---	---
Sulfide	1.6 - 3.3	1.6 - 3.3
Minor and Trace Elements (µg/l)		
Aluminum	---	---
Arsenic	0.20 - 20	0.20 - 20
Barium	0.6 - 1.0	0.08 - 0.13
Beryllium	---	---

(continued)

TABLE 23 (continued)

	Enrichment factors	
	Leachate	Leachate
	Upper Aquifer	Lower Aquifer
Minor and Trace Elements (μg/l) (continued)		
Boron	0.4 - 12	0.01 - 0.3
Bromine	---	---
Cadmium	0.3 - 0.6	0.6 - 1.2
Chromium	0.01 - 4	0.4 - 130
Cobalt	---	---
Copper	0.14 - 2.9	0.14 - 2.9
Fluoride	0.001 - 11	0 - 4
Iron	0.12 - 6	0.8 - 3.8
Lead	---	---
Manganese	0.6 - 5	0.6 - 5
Mercury	0.10 - 0.8	0.15 - 0.8
Molybdenum	1.5 - 4,000	4 - 1,500
Nickel	2.5 - 30	5 - 60
Rubidium	---	---
Scandium	---	---
Selenium	0.5 - 200	0.5 - 200
Silver	---	---
Thallium	---	---
Titanium	---	---
Uranium	---	---
Vanadium	1.5 - 50	0.19 - 6.3
Zinc	0.1 - 15	0.1 - 15
Gross Organic Parameters		
TOC	10 - 550	3 - 170
Phenolics	---	---

The uncertainty in the enrichment factors reflects variations in the original oil shale, methods of retorting, methods of analysis, and emphasizes the necessity of preliminary controlled experiments prior to finalizing monitoring programs. Enrichment factors for those elements which are present in concentrations near the detection limit, such as Se, would also be expected to give variable enrichment factors.

Table 24 presents enrichment factors for retort waters and is relevant to the extent that an in situ retort is not completely burned and retains a fraction of the retort water. Most notably enriched in the retort water are NH_4^+, $CO_3^=$, As, Br, Co, Hg, Se, V, U, and TOC, and possibly NO_3^-, PO_4^{3-}, and Ni. The sulfur species shown at the bottom of the table will be discussed in the next subsection.

Although $CO_3^=$ is enriched in retort waters, it is unlikely that this species would successfully pass through a spent retort because of the reaction:

$$Ca^{2+} + CO_3^= = CaCO_3$$

In fact, Parker et al. (1977) have shown that spent shale does, in fact, remove carbonate from surface waters. NH_4^+, on the other hand, is likely a highly mobile species, possibly after conversion to nitrate. In addition, the more hydrophilic portions of the TOC may also travel with leachate and prove indicative of groundwater contamination.

As in leachates from spent shale, retort waters appear enriched in those species forming soluble anions, such as As, Br, Se, and U. The origin of Co, Hg, and V in the retort waters is less clear, although V is known to form organic complexes with organic compounds found in crude petroleum oils, and Hg is known to vaporize from a simulated in situ retort and to recondense later (Fox et al., 1978).

In summary, the water quality parameters pH, TDS, Cl, Na, SO_4, Mo, Se, NH_4, Br, Se, V, U, and TOC should be considered as potentially valuable indicators of groundwater contamination, both for their elevated enrichment factors and for chemical reasons.

The utility of enrichment factor estimates is the identification of chemical species likely to be detected in groundwater which indicate the impact of a known source. To evaluate this possible monitoring approach, the enrichment factors calculated above were categorized (arbitrarily) as follows:

Table 25 category	Enrichment factor range	Relative likelihood of detection of impact
1	>500	High
2	50 - 500	Moderate
3	10 - 50	Low

TABLE 24. ENRICHMENT FACTORS FOR RETORT WATERS

	Enrichment factors	
	Leachate Upper Aquifer	Leachate Lower Aquifer
Gross Parameters (mg/l)		
Conductance	10 - 130	2.1 - 27
Alkalinity	19 - 130	2.4 - 17
pH	1.0 - 1.6	1.0 - 1.2
TDS	1.8 - 25	0.3 - 4
Ammonium	3,400 - 26,000	170 - 1,300
Bicarbonate	34 - 62	4 - 8
Calcium	0.01 - 1.2	0.002 - 0.31
Carbonate	170 - 10,000	25 - 1,600
Chloride	0.002 - 80	0.001 - 40
Cyanide	40 - 90	40 - 90
Magnesium	0.001 - 5	0.01 - 20
Nitrate	0.17 - 120	0.34 - 240
Potassium	1.5 - 35	0.15 - 3.5
Silica	0.02 - 8	0.04 - 15
Sodium	0.001 - 22	~0 - 1.7
Sulfate	0.06 - 5.4	0.3 - 30
Phosphate	0.8 - 1,000	0.8 - 1,000
Kjeldahl nitrogen	1,700	---
Sulfide	0.17	0.17
Minor and Trace Elements (μg/l)		
Aluminum	---	---
Arsenic	2.4 - 600	2.4 - 600
Barium	0.2 - 7	0.003 - 0.9
Beryllium	---	---
Boron	0.26 - 9	0.01 - 0.22
Bromine	0.4 - 50	0.04 - 5
Cadmium	0.1 - 1.6	0.20 - 3.2
Chromium	0.07 - 60	2.0 - 12
Cobalt	0.4 - 130	0.7 - 220

(continued)

TABLE 24 (continued)

	Enrichment factors	
	Leachate Upper Aquifer	Leachate Lower Aquifer
Minor and Trace Elements (μg/l) (continued)		
Copper	0.04 - 1.3	0.04 - 1.3
Fluorine	0.05 - 9	0.02 - 3
Iron	0.00001 - 15	0.001 - 100
Lead	0.05 - 10	0.4 - 10
Manganese	0.23 - 1.4	0.23 - 1.4
Mercury	3.3 - 1,000	5 - 1,000
Molybdenum	2 - 11	2 - 11
Nickel	3 - 50	6 - 100
Radiation, beta	9 - 35	1.8 - 7
Scandium	---	---
Selenium	>0.5 - >170	>0.5 - >170
Silver	---	---
Thallium	---	---
Titanium	2 - 21	2 - 21
Uranium	>0.33 - >150	>0.50 - 230
Vanadium	2 - 5,500	0.25 - 700
Zinc	0.20 - 25	0.20 - 25
Lithium	---	---
Organic Parameters		
TOC	10,000	3,000
Unusual Sulfur Species		
Total sulfur	6 - 20[a]	35 - 120[a]
Thiosulfate	1,200 - 6,400[b]	1,200 - 6,400[b]
Tetrathionate	400[b]	400[b]
Thiocyanate	65 - 2,000[b]	65 - 2,000[b]

Notes:

[a] Calculated by assuming that all S in groundwaters is present as sulfate.

[b] Calculated by assuming background concentrations equal to a detection limit of 0.5 mg/l.

TABLE 25. RELATIVE LIKELIHOOD OF DETECTION OF MOBILITY FROM VARIOUS SOURCES TO UPPER AND LOWER AQUIFERS AND SPRINGS BASED ON ESTIMATED ENRICHMENT FACTORS

Constituent	Lower to Upper Aquifer	Lower Aquifer to springs	In situ leachate to Upper Aquifer	In situ leachate to Lower Aquifer	Retort water to Upper Aquifer	Retort water to Lower Aquifer
General water quality measures						
Conductivity	---	---	2	3	2	3
Total dissolved solids	---	---	2	3	3	---
Alkalinity	---	---	---	---	2	3
Major inorganic ions						
Calcium	---	---	2	3	---	---
Magnesium	---	---	2	2	---	3
Potassium	3	3	2	---	3	---
Sodium	3	3	2	3	3	---
Chloride	---	---	2	2	2	3
Sulfate	---	---	2	1	---	3
Fluoride	---	3	3	---	---	---
Bicarbonate	---	---	---	---	2	---
Carbonate	---	---	1	2	1	1
Ammonia	3	3	---	---	1	1
Nitrate	---	---	---	---	2	2
Phosphate	---	---	---	---	1	1
Silica	---	---	---	---	---	3
Organics						
Total organic carbon	---	---	1	2	1	1
Phenolics	3	3	---	---	---	---
Kjeldahl nitrogen	---	---	---	---	1	---
Cyanide	---	---	---	---	2	2

(continued)

TABLE 25 (continued)

Constituent	Lower to Upper Aquifer	Lower Aquifer to springs	In situ leachate to Upper Aquifer	In situ leachate to Lower Aquifer	Retort water to Upper Aquifer	Retort water to Lower Aquifer
Sulfur species						
Total sulfur	---	---	---	---	3	2
Thiosulfate	---	---	---	---	1	1
Tetrathionate	---	---	---	---	2	2
Thiocyanate	---	---	---	---	1	1
Trace elements						
Arsenic	---	---	3	3	1	1
Barium	---	3	---	---	---	---
Boron	3	2	3	---	---	---
Bromide	3	3	---	---	3	---
Chromium	---	---	---	2	2	3
Cobalt	---	---	---	---	2	2
Iron	---	---	---	---	3	2
Lead	---	---	---	---	3	3
Mercury	---	---	---	---	1	1
Molybdenum	---	---	1	1	3	3
Nickel	---	---	3	2	3	2
Selenium	---	---	2	2	2	2
Titanium	---	---	---	---	3	3
Uranium	---	---	---	---	2	2
Vanadium	---	---	3	---	1	1
Zinc	---	---	3	3	3	3
Radiological						
Gross beta	---	---	---	---	3	---

Note:

[a] Enrichment factor (EF) categories: 1 = high likelihood of detection (EF > 500); 2 moderate likelihood (EF = 50 to 500); relatively low likelihood (EF = 10 to 50).

The results of this categorization are shown in Table 25.

For monitoring in the Upper Aquifer for the impact from two major in situ sources, consider the following listing:

	Water quality constituent	
Potential source of impact	Enrichment factor >500	Enrichment factor 50 - 500
Retort water	Carbonate	Conductivity
	Ammonia	Alkalinity
	Phosphate	Chloride
	TOC (or DOC)	Bicarbonate
	Kjeldahl N	Nitrate
	Thiosulfate	Cyanide
	Thiocyanate	Tetrathionate
	Arsenic	Chromium
	Mercury	Cobalt
	Vanadium	Selenium
		Uranium
In situ spent shale leachate	Carbonate	Conductivity
	TOC (or DOC)	TDS
	Molybdenum	Calcium
		Magnesium
		Potassium
		Chloride
		Sulfate
		Selenium

Examination of this listing indicates that the following constituents may be unique indicators of the impact of retort water or spent shale leachate on the Upper Aquifer. A unique indicator is one which is in the above listing for one source, but not for the other:

Possible unique indicators	
Retort water	In situ spent shale leachate
Alkalinity	TDS
Bicarbonate	Calcium
Ammonia	Magnesium
Phosphate	Potassium
Nitrate	Sodium
Kjeldahl N	Sulfate
Thiosulfate	Molybdenum
Thiocyanate	
Tetrathionate	
Cyanide	
Arsenic	
Chromium	
Cobalt	
Mercury	
Uranium	
Vanadium	

Following the same procedure for consideration of monitoring in the Lower Aquifer, the following listing was extracted from Table 25:

	Water quality constituent	
Potential source of impact	Enrichment factor >500	Enrichment factor 50 - 500
Retort water	Carbonate	Nitrate
	Ammonia	Cyanide
	Phosphate	Total sulfur
	TOC	Tetrathionate
	Thiosulfate	Cobalt
	Thiocyanate	Iron
	Arsenic	Nickel
	Mercury	Selenium
	Vanadium	Uranium

(continued)

	Water quality constituent	
Potential source of impact	Enrichment factor >500	Enrichment factor 50 - 500
In situ spent shale leachate	Molybdenum	Chloride Carbonate TOC Chromium Nickel Selenium

Possible unique indicators were then identified from this listing:

Possible unique indicators	
Retort water	In situ spent shale leachate
Ammonia	Sulfate
Phosphate	Magnesium
Nitrate	Chloride
Tetrathionate	Chromium
Thiosulfate	Molybdenum
Thiocyanate	
Arsenic	
Cobalt	
Iron	
Mercury	
Uranium	
Vanadium	

Indicator Constituents

In addition to those water quality parameters for which baseline values have been established, additional species have been measured on a random basis in oil shale effluents. These species will be discussed in this subsection.

Inorganic Species--

Data presented earlier suggest that those trace elements forming stable, soluble anions under basic, oxidizing conditions are most likely to be enriched in leachates from a spent in situ retort. It is thus interesting to speculate whether additional elements not discussed above may behave similarly. Other trace elements which form anions under basic, oxidizing conditions include Te, Sb, Bi, Po, W, Re, and I, and their monitoring may prove valuable. However, a more complete investigation of the geochemistry of these species is beyond the scope of this book and their potential mobility remains speculative.

Species such as SCN^-, $S_2O_3^=$, and $S_4O_6^=$ are normally not detectable in groundwater and should, therefore, form excellent indicators of groundwater contamination. Since background concentrations of these species have not been measured, enrichment factors (Table 21) were calculated using estimated detection limits as background concentrations, based on the assumption that their concentrations were less than the detectable limit. The enrichment factors shown in Table 21 for these species recommend them as possible tracers of groundwater contamination, especially if even lower detection limits can be achieved.

Organic Species--

The enrichment factors for TOC (or DOC) for both leachates and retort water suggest organic matter as a valuable indicator. However, the baseline organic content of groundwater actually varies widely; Leenheer and Huffman (1976), for example, indicate levels of DOC of 30,700 mg/l for trona water collected near Eden, Wyoming. Few measurements in the Piceance Basin have been greater than about 10 mg/l. Leachates from raw shale may contain more organic acids than leachates from spent shale.

For these reasons, individual organic compounds (or compound classes) which are absent in natural groundwater, but which are produced by the retorting process, should prove to be more sensitive probes of groundwater movement. For this reason, organic (DOC) fractionation methods, such as those described by Leenheer and Huffman (1976), may provide a set of useful indicators for monitoring.

One such type of organic compound could be aromatic acids, which are enriched in leachate from spent shale compared to raw shale. In addition, the smaller (lower molecular weight) aromatic acids should be highly soluble in the basic conditions expected and should, therefore, follow water movement closely. The larger acids, although ionized, could be more readily sorbed and, therefore, migrate less slowly. Polynuclear aromatic hydrocarbons, which are products of combustion, may also increase during combustion.

Another likely organic tracer would be in hydrophilic bases. Much interest has focused on such compounds lately because of their biological activity and unusually large occurrence in oil shale products. Fruchter et al. (1977), for example, have found that indoles, substituted pyridines, quinolines, and acridines are highly enriched in shale oil as compared to coal-derived syncrude. Sievers and Denny (1978) have also detected numerous organic bases, many of which could not be readily identified, in retort waters. To the extent that such organic bases are retained by groundwater, they should provide sensitive and unusual indicators of groundwater contamination.

Stable Isotopes

It is well established that variations in isotopic abundances--especially for the light elements--occur naturally through such processes as diffusion, evaporation, dissolution, and chemical reaction. For example, ^{13}C is about 3 percent more abundant in ocean bicarbonate than in terrestrial petroleum (Roboz, 1968).

Similar variations in the isotopic ratios of other light elements, such as H, N, O and S, suggest this measurement as a probe for studying the migration of groundwater. As an example, suppose the $^{2}H/^{1}H$ ratio is slightly higher in kerogen than in natural groundwater. Water produced by combusting kerogen will thus be labeled with a higher $^{2}H/^{1}H$ ratio and could be distinguished from natural groundwater. Similar considerations should be given to natural and combustion-produced NH_4^+, $CO_3^=$, and $SO_4^=$.

The variation in stable isotope abundances is normally reported as parts per thousand variation from a standard:

$$\delta = \frac{(I_2/I_1)_{\text{sample}} - (I_2/I_1)_{\text{standard}}}{(I_2/I_1)_{\text{standard}}}$$

where I_2 and I_1 refer to the minor and major isotope, respectively.

Variations in isotope ratios are measured almost exclusively by mass spectrometry. Although any mass spectrometer is capable of measuring isotope ratios, the measurement of naturally occurring variations requires highly specialized instruments. Indeed, many isotope ratio mass spectrometers are dedicated to a single element. Consequently, such instruments are found almost exclusively in research laboratories and are numerically absent from commercial laboratories.

Isotope ratio mass spectrometers are characterized by dual detector systems which are designed to collect both isotopes simultaneously, thereby minimizing errors due to ion current instability. Detector electronics are specifically designed to yield the isotope ratio directly, and ion sources typically include a means of switching rapidly between the sample and a standard of known isotopic composition. The precision with which δ may be measured in a routine matter is about 1 mil for H and 0.1 mil for C, O, and N. The precision of δ is typically limited by isotope fractionation which occurs during sample preparation and introduction into the mass spectrometer.

Although studies of isotope ratios in the Green River Formation have not been found in the literature, other relevant investigations deserve mention. Friedman et al. (1964), for example, discuss the natural variations of deuterium in the hydrologic cycle, including the theory of the fractionation processes which occur during evaporation, transport, and deposition. They also report the results of over 1,000 determinations of ^{2}H in waters of North America. Dansgaard (1964) also discusses both the theory and the measurements of ^{2}H and ^{18}O in precipitation.

Holt et al. (1972) and Jensen and Nakai (1961) both discuss natural variations of ^{34}S in environmental samples. Holt et al. (1972) observed perturbations of $\delta^{34}S$ in surface waters due to rainfall, earth-surface disturbances, and effluents from sewage treatment plants.

N isotopic ratios have been studied widely, principally as a means of identifying pollutant sources and characterizing the atmospheric N cycle (Moore, 1977; Moore, 1974; Hoering and Moore, 1958; Wada et al., 1975). Naturally occurring values of $\delta^{15}N$ ranging from -15 to +25 have been observed.

Possible problems which may be encountered in the application of the stable isotope technique to the Green River Formation include lack of background data, insufficient difference in δ for natural and contaminated groundwater, and exchange reactions such as the following:

$$^{1}H_2HO + {}^{1}HCO_3^- \rightarrow {}^{1}H_2O + {}^{2}HCO_3$$

$$H_2{}^{18}O + HC^{16}O_3^- \rightarrow H_2{}^{16}O + HC^{18}O^{16}O_2^- \; .$$

Thus, to the extent that carbonates and bicarbonates exchange with, or precipitate as solid materials, the isotopic composition of certain elements may be altered.

SAMPLE ANALYSIS AND COSTS

This discussion is meant to aid the reader in the efficient selection of analytical techniques suitable for monitoring groundwater movement. Both survey and element-specific techniques are discussed.

Trace Elements

The most common techniques which are used for trace element analysis are instrumental neutron activation analysis (INAA), inductively coupled plasma emission spectroscopy (ICP), spark source mass spectroscopy (SSMS), and atomic spectroscopy with its various modifications (AA). Each technique has strengths and weaknesses which should be recognized.

Table 26 compares these techniques on the basis of their abilities to detect trace levels of 44 elements. Although not shown on the table, the limit for SSMS is typically 1 µg/l for most elements. The detection limits for ICP were obtained from a recent review of an ICP spectrometer in use at a DOE synfuels laboratory, and were determined with artificial, multielement standards. The detection limits shown for a flameless (carbon rod) and flame AA were taken from the manufacturer's literature. The limits for INAA were for a routine survey available on a commercial basis. The working limits shown in the table are the lowest concentrations typically reported by a routine analytical services laboratory located in Denver. In this case, the working limits are typically several times the detection limit, since the method of choice in an analytical services laboratory is determined by regulatory requirement,

TABLE 26. COMPARISON OF ANALYTICAL TECHNIQUES FOR TRACE ELEMENT DETERMINATIONS[a]

	Detection limits				Working limit, Denver Laboratory		Colorado water quality standards cleanest classification
Element	ICP (µg/l)	Flameless AA (µg/l)	Flame AA (µg/l)	Instrumental Neutron Activation Analysis[b] (µg/l)	(µg/l)	Method[c]	(µg/l)
Ag	3	0.03	2	0.5	0.05	B	0.1
Al	3	2	20	100	100	A	100
As	16	15	100, 2[d]	0.5	2	B	50
B	15		2,000	NA	50	C	750
Ba	1	2	20	100	50	A	1,000
Be	1	0.2	0.7	NA	5	A	10
Bi	80	1.4	46	NA	500	A	---
Ca	2	0.06	2	1,000	50	A	---
Cd	15	0.02	0.7	0.10	2	A	0.4
Co	5	0.8	7	0.5	10	A	---
Cl	---	---	---	500	200	C	---
Cr	3	0.5	5	2	10	A	50
Cu	4	0.4	2	300	10	A	10
Ga	30	2	40	~70	---	---	---
Ge	20	---	100	NA	---	---	---
Fe	5	0.5	6	200	10	A	300
F	---	---	---	200	100	D	---

(continued)

TABLE 26 (continued)

Element	Detection limits				Working limit, Denver Laboratory		Colorado water quality standards cleanest classification
	ICP (µg/l)	Flameless AA (µg/l)	Flame AA (µg/l)	Instrumental Neutron Activation Analysis[b] (µg/l)	(µg/l)	Method[c]	(µg/l)
Hg	600	12	0.4[b]	0.5	0.02	d	0.05
K	50	0.2	2	300	100	A	---
Li	50	0.4	2	NA	5	A	---
Mg	1	0.006	0.2	5,000	50	A	125,000
Mn	5	0.04	2	20	5	A	50
Mo	7	0.6	30	3	5	B	---
Na	90	0.02	0.3	70	100	A	---
Nb	30	---	3,000	~25,000	---	---	---
Ni	9	1	8	NA	10	A	50
P	30	---	---	NA	100	C	---
Pb	20	0.3	15	NA	1	B	4
Sb	60	3	40	0.5	50	A	---
Se	20	6	250, 2[d]	1	5	B	10
Si	30	7	200	NA	1,000	C	---
Sn	12	1	30	80	500	A	---
Sr	10	0.8	2	2,000	10	A	---
S	---	---	---	NA	---	---	---

(continued)

TABLE 26 (continued)

Element	Detection limits ICP (μg/l)	Flameless AA (μg/l)	Flame AA (μg/l)	Instrumental Neutron Activation Analysis[b] (μg/l)	Working limit, Denver Laboratory (μg/l)	Method[c]	Colorado water quality standards cleanest classification (μg/l)
Te	5	---	40	2	---	---	---
Ti	1	---	50	200	300	A	---
Th	---	---	---	0.2	---	---	---
Tl	200	0.6	13	NA	5	B	15
U	500	1,000	60,000	1	2	E	30
V	2	10	50	1	5	A	---
Zn	10	0.02	1	10	5	A	50
W	---	---	---	30	---	---	---
Br	---	---	---	1	---	---	---
I	---	---	---	30	---	---	---

Notes:

[a] Detection limits correspond to approximately 20 times the background noise level. Working limits typically correspond to several times the background noise level and are based on a wide variety of groundwater and surface water using equipment in a routine fashion.

[b] Note INAA not approved EPA method.

[c] A - flame atomic absorption; B - carbon rod atomic absorption; C - colorimetric; D - electrode; E - fluorometric.

[d] Vapor generation.

NA - not available under normal circumstances or very insensitive.

economics, and ease of operation. It should be recognized that data in Table 26 represent a common basis for discussion; however, detection limits are often degraded in complex samples or improved by special pretreatment processes.

In addition to the detection limits, the precision and importance interferences should be considered. ICP is relatively free of matrix interferences, but is subject to spectral interferences. For example, the DOE operators have reported poor accuracy for U, Co, As, and Cd on complex samples, presumably because of spectral interferences. AA has fewer spectral interferences, but special corrections may be needed for background or matrix interferences. The precision of AA or ICP spectroscopy is typically ±10 percent when used by trained personnel. INAA is often considered a reference method for trace elements because of its relatively high precision at trace levels and freedom from matrix interferences. SSMS is typically subject to fewer interferences than either ICP or AA, but the routine precision for this technique is about ±40 percent, although precisions of ±3 percent have been reported in the literature using electrical detection under tightly controlled conditions. Since samples for SSMS must be dried onto a graphite substrate and placed in a vacuum, volatile elements such as Hg, S, and Se may be lost, especially under acidic conditions.

It is obvious that no single method is a panacea. INAA is attractive because of its detectability for the potential low-level indicators As, Sb, Se, Te, U, and V. SSMS is favored as a survey technique because it provides uniformly low detection levels and broad elemental coverage. The other methods listed in Table 26 are attractive as monitoring tools because of their adequate precision and detectability for many elements.

Organic Methods

Common techniques which are available for the determination of trace organic species in complex mixtures include gas chromatography (GC), combined gas chromatography/mass spectroscopy (GC/MS), high-pressure liquid chromatography (HPLC), and thin-layer chromatography (TLC). Recent advances in controlling the variables in TLC are also giving rise to high-performance, thin-layer chromatography (HPTLC).

Standardized methods are not normally available for specific organic compounds since operating parameters are optimized for each substrate and analyte.

For more tractable species, literature references may be found for similar substrates, although as a general rule a significant effort will be required for implementing, adapting, and "debugging" methods for groundwater in the oil shale area. Organic bases are a particular problem since they readily decompose and since analytical methods are poorly developed.

Instrumentation should include a GC, GC/MS, and HPLC as a minimum, along with other standard analytical equipment. The GC/MS should be capable of operating with capillary columns and be capable of peak switching and single ion monitoring. A specific nitrogen detector on the GC should be considered essential for the determination of organic bases (Sievers and Denny, 1978).

Nonspecific separation schemes are also available for classifying the types of organic compounds in water (Hamersma et al., 1976; Leenheer and Huffman, 1976). Such schemes can provide a first warning of the groundwater changes and can indicate otherwise unsuspected changes. The procedures by Leenheer and Huffman may be of special interest since it was originally conceived as an aid in understanding the movement of organic materials in groundwater. The procedure operates by separating hydrophilic and hydrophobic acidic, basic, and neutral compounds based on their adsorptive characteristics on artificial resins. In this scheme, the hydrophilic fractions should be most mobile in groundwater, while the hydrophobic fractions should most readily be retained by sorptive clays and minerals.

Other Inorganic Species

For a wide variety of commonly occurring inorganic species, standard methods have been developed and tested which are reliable when applied to typical surface water or groundwater and which can be performed with a minimum of equipment (U.S. EPA, 1974; American Public Health Association, 1976; U.S. Geological Survey, 1970). Although standard methods must not be applied blindly to oil shale waste water (or to other waste water), it is believed that many standard methods can be modified slightly in order to produce more reliable results. In any case, a carefully designed quality assurance program is highly recommended.

This subsection first discusses several representative standard analytical procedures, analytical problems which occur, and possible solutions. A discussion of possible additional procedures which could be used to better or more efficiently analyze oil shale waste waters then follows.

Total Suspended and Dissolved Solids--

Normally, these are determined by drying an aliquot of water at 103° to 105°C. In retort waters, this may cause the loss of ammonium carbonate and result in an artificially low result. A possible solution is evaporation at a different pressure and temperature to more selectively remove the water, or complete evaporation of ammonium carbonate, which is then determined separately.

Alkalinity--

Normally, alkalinity is measured by titrating with dilute acid. Results are typically interpreted as total bicarbonate and carbonate. In retort waters, dissolved ammonia and organic acids are also titrated so that the results should be interpreted as "total titratable base." Another method is to determine carbonate and bicarbonate by measuring total inorganic carbon in a TOC analyzer and adjusting the pH and ionic strength. Other options include acidification of the sample and determination of the evolved CO_2 titremetrically, colorimetrically, or by hydrogenation and the detection of methane.

Chloride--

Chloride is often determined by the subsequent reactions in a continuous flow system:

$$2Cl^- + Hg(SCN)_2 \rightarrow HgCl_2 + 2SCN^-$$

$$SCN^- + Fe^{3+} \rightarrow Fe(SCN)_x \ .$$

The colored ferric thiocyanate complex is then detected colorimetrically. In retort water, thiocyanate is thus detected as chloride. This problem should be removed by chemically oxidizing the thiocyanate prior to analysis. Alternatively, analyzing subsequent samples with and without the addition of $Hg(SCN)_2$ may provide a determination for both chloride and thiocyanate.

pH--

pH electrodes are subject to fouling by oils. This common problem can be overcome by frequent standardization or a cross check with a series of pH indicators, which are certainly as accurate, if not as convenient.

Nitrate--

Often nitrate is determined by the automated Cd reduction method. A common problem is the fouling of the Cd reduction column by organic materials. A possible solution is extraction of the organic material prior to analysis, or the use of an alternate reducing agent, such as hydrazine.

BOD--

In our experience, the normal BOD determination is not reproducible unless acclimated seed is used.

Ammonia--

Often ammonia is determined with a selective ion electrode (which is subject to fouling by organic materials). A likely solution is removal of the organic materials by extraction, by filtration with a hydrophilic filter, or by the use of macroreticular resins.

Other Constituents--

It is likely that similar problems and relatively straightforward solutions may exist for other assays, such as fluoride and sulfate. Such minor modifications may be simple and, indeed, are often practiced by the alert analytical chemist. There are, of course, requirements for entirely new or greatly improved analytical methods. Possible analytical schemes are discussed below as examples.

Determination of the complex mixture of sulfur and nitrogen species found in retort waters is an unresolved problem. In addition, S, $S_2O_3^{=}$, $S_4O_6^{=}$, $S_3O_6^{=}$, $SO_4^{=}$, SCN^-, and CN^- can interract and thereby change their chemical form. SCN^- can further react with oxidizing agents, which might be used in water treatment, to form the highly toxic cyanogen chloride.

One approach which has been used (Stuber et al., in press) for this problem is the cyanolysis of the various sulfur oxides with selective catalysts (Kelly et al., 1969). The resulting SCN^- was detected colorimetrically as the ferric thiocyanate complex. However, it has not yet been shown that the catalysts are sufficiently selective or that they do not occur naturally in sufficient quantities in waste waters.

There are several possible approaches to this problem which would be considered:

- Ion chromatography
- The development of coloring agents specific for thiosulfate, thiocyanate, tetrathionate, etc.
- Polarographic techniques which distinguish between the various S and N species on differing oxidation potentials
- Surrogate tests.

The latter tests assume that speciation of the various forms of S and N is not essential. As an example, $S_2O_6^{=}$, $S_3O_6^{=}$, and $S_4O_6^{=}$ could be determined as a group using the cyanolysis procedure of Kelly et al. (1969).

An especially attractive technique for such complex waters is ion chromatography. Because it is a separatory technique, complex and selective reactions are not required. Ion chromatography holds the possibility of chromatographically determining cyanide, thiocyanate, sulfate, thiosulfate, trithionate, tetrathionate, sulfide, as well as phosphate, fluoride and nitrate, minutes after sample collection. Because ion chromatography detects ions nonselectively, the presence of unexpected peaks alerts the analysts to unknown ions. Thus, the analyst can often detect previously unexpected compounds.

At the other extreme are tests which would measure, for example, total sulfur in all forms. Such a technique could be used to alert the analysts to the need for a more detailed analysis of sulfur species.

INTERPRETATION OF WATER QUALITY DATA

Data Analysis

Data analysis procedures include (1) checks on data validity, and (2) methods for presenting data for interpretation for environmental description or control purposes. Data checking procedures include:

- Cation-anion balance
- TDS-conductivity comparison
- Conductivity-ion comparison (meq/l)
- Diluted-conductance method.

The cation-anion balance check involves considering the theoretical equivalence of the sum of the cations (expressed in milliequivalents per liter (meg/l)) and the sum of the anions (in meq/l). Because of variations in analysis which may be unavoidable, exact equivalence is seldom achieved. In general, the inequality observed can be expected to increase as the total ionic concentration increases. When using this method, it is assumed that analyses of all significant ions have been included and that the nature of the ionic species is known. In addition, it should be noted that compensating analytical errors can fortuitously produce a close ion balance. Hence, a combination of quality control (e.g., replicate analyses, use of standard references, spiked samples, etc.) and data checking procedures should be employed.

For other analysis checks, samples can be evaporated to dryness at 180°C and the weight compared to the total solids determined by calculation. This check is approximate because losses may occur during drying by volatilization and other factors may cause interference (Brown, Skougstad, and Fishman, 1970). Another recommended check on analyses involves multiplying specific conductance (µmhos/cm) by a factor ranging from 0.55 to 0.75. The product should approximately equal total dissolved solids, in mg/l, for water samples with TDS below 2,000 to 3,000 mg/l. Also, the specific conductance divided by 100 should approximately equal the meq/l of anions or cations. This relationship is useful in deciding on which sum, cations or anions, is in error. A more refined method for checking TDS by the electrical conductivity relationships, called the diluted-conductance method, may also be employed.

Proper design of the monitoring program with regard to selection of monitoring sites, sampling frequency and analytical methods, and implementation of quality control measures will alleviate such data interpretation problems. Good monitoring design can deal effectively with sources of data variability, such as operational variability of field instrumentations and errors in calculations or analysis.

Other significant sources of data variability are events such as in-plant spills, poor in-plant housekeeping practices, temporary process or control equipment failure or modification, and other in-plant events. These events may be entirely random (e.g., spills) or somewhat cyclic (e.g., equipment maintenance) in nature. Effectively dealing with these sources of data variability requires liaison with facility operators. Ideally, this communication should be of two types, namely to assure that (1) monitoring personnel have adequate knowledge of facility operations (and deviations), and (2) that plant developers have access to monitoring data and the evaluations made of that data. Such intercommunication can enhance data interpretation efforts.

Data Presentation

Data presentation and interpretation are key aspects of monitoring for environmental detection and control. Several methods are available for organization and presentation of water quality data. These include tabulation and graphical tabulation of appropriate water quality criteria or standards, providing a format for screening data and identifying important sites or pollutant constituents. Ionic concentrations can be expressed as milligrams per liter or milliequivalents per liter. Other water quality measures may be segmented into contributing components, such as total and noncarbonate hardness or phenolphthalein and methyl orange alkalinity.

Graphic representations of analyses of the chemical quality of water are useful for display purposes, for comparing analyses, and for emphasizing similarities and differences. Graphs can also aid in detecting the mixing of waters of different composition and in identifying chemical processes occurring as water moves through the hydrologic regime of the monitoring area. A variety of graphic techniques is available; some of the more useful ones are described in the following paragraphs.

A widely used method of data presentation is the bar graph. On a bar graph, each sample analysis appears as a vertical bar whose total height is proportional to the total concentration of anions and cations, expressed in milliequivalents per liter. One-half of the bar represents cations and the other half anions. These segments are divided horizontally to show the concentrations of major ions or groups of closely related ions, which are shown by distinctive patterns. Variations include the addition of individual bar graphs to express levels of other water quality measures, such as hardness or un-ionized solutes such as silica.

Water quality data can also be plotted as a set of radiating vectors (Figure 36). Related methods of showing concentrations as linear vectors result in constructions of polygons. These approaches are useful in displaying changes in water quality as changes in, for example, the shape of these polygons. Trilinear diagrams are another useful method for representing and comparing water quality analyses (Figure 37).

Here, cations, expressed in percentage of total cations (as milliequivalents per liter), plot as a single point on the left triangle. Anions, similarly expressed as a percentage of total anions, appear as a point in the right triangle. These points are then projected into the central, diamond-shaped area parallel to the upper edges of the central area. This single point is thus uniquely related to the total ionic quality, and at this point a circle can be drawn with an area proportional to the total dissolved solids concentration. The trilinear diagram is a convenient way to distinguish similarities and differences among various water samples as waters with similar qualities will tend to plot together as groups. Also, simple mixtures of waters can be identified as the mixture data will plot at locations intermediate between the mixture component waters.

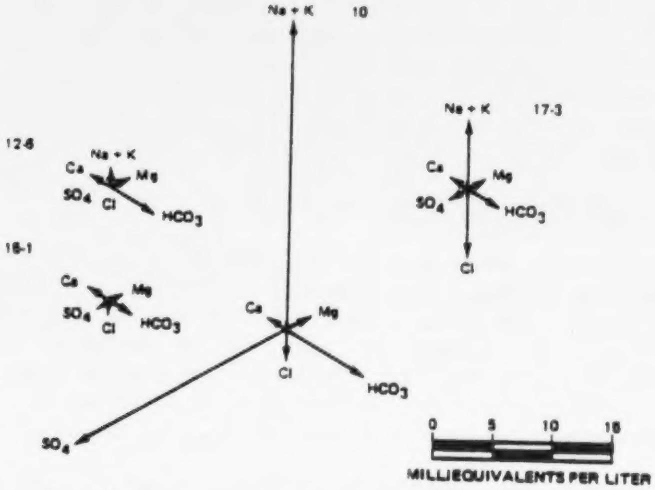


Figure 36. Water quality data display using vectors.

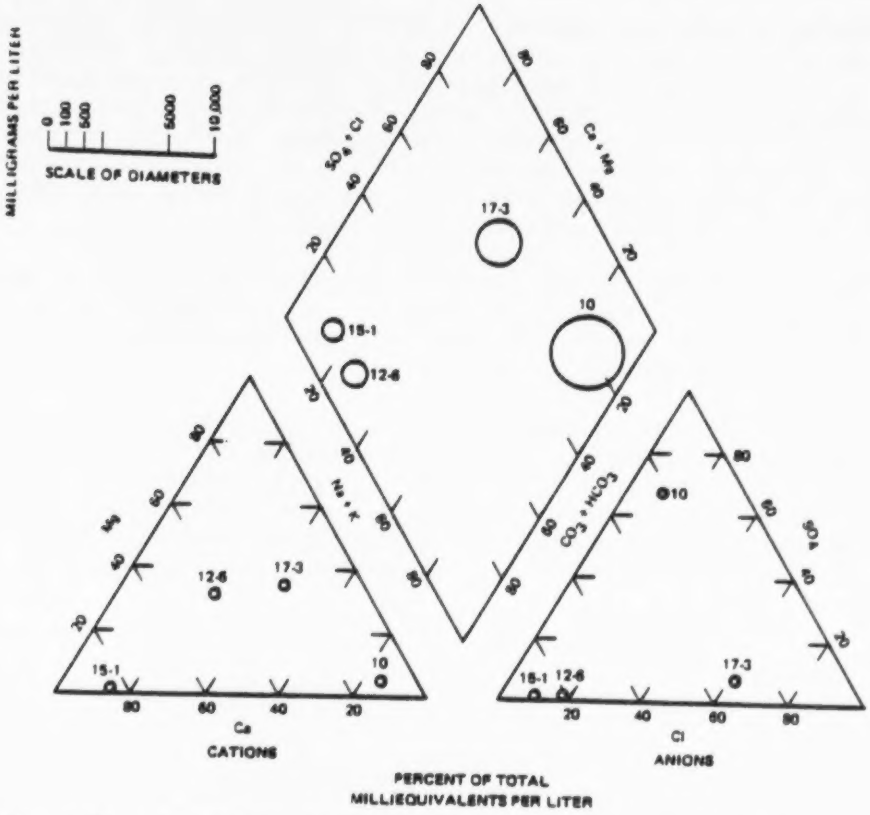


Figure 37. Trilinear diagram for displaying water quality data.

Other graphic methods include time series plots, plots of variation in water quality constituents with distance or depth, area or cross-section plots of equal water quality lines, and plane maps. The choice of data presentation is determined by the goals of the monitoring program and the type of audience to which the data are to be presented. The goal of data presentation is to provide a clear portrayal of the data for evaluation of environmental quality.

Data Interpretation and Reporting

Water quality data from monitoring should be analyzed and interpreted so as to define quality trends, identify new pollution problems or regions of improvement, and assess the effectiveness of pollution control activities. Assessments include such things as identifying segments of the groundwater systems not meeting water quality standards and projections of impact on various water uses. The monitoring program should incorporate pertinent data from all agencies and organizations involved in the monitoring region.

The final result of a monitoring program organized in an area is information on water quality. The final task of the monitoring program is to disseminate the information gained in usable forms to the agencies and organizations concerned with such information.

Monitoring should be summarized in appropriate forms for convenient study before wide distribution outside of the monitoring agency. This may involve preparation of tables showing averages and/or changes in water quality. Similarly, graphs prepared to readily display long-term trends may be helpful, as described previously. Maps showing, for example, locations of major known sources of pollution, areal distribution of concentrations of key pollutants, and regions having groundwater with qualities not meeting some water quality criterion can also be shown to be both useful and effective.

Monitoring information should be distributed regularly to appropriate public agencies--local, State, and Federal. Major industries in the area should also receive the material as well as cooperating agencies and organizations that contribute monitoring data.

Finally, the monitoring agency would have the responsibility to alert action and enforcement agencies of critical problems or situations which are discovered within the monitoring program. This may involve, for example, detection of hazardous or toxic pollutants which could affect water users. Prompt reporting of such instances is essential, as is following up with specialized monitoring efforts for documenting and controlling emergency situations.

REFERENCES

Ahrens, T.P., and A.C. Barlow, Permeability Tests Using Drill Holes and Wells, Including Comments Regarding Equipment, Etc., Bureau of Reclamation Geology Report No. G-97, 1951.

American Public Health Association, Standard Methods, 19th Edition, Washington, D.C., 1976.

Brown, E., M.W. Skougstad, and M.J. Fishman, "Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases," Techniques of Water-Resources Investigation, Book 5, Chapter A-1, U.S. Geological Survey, 1970.

Bureau of Reclamation, Ground Water Manual, U.S. Department of Interior, 1977.

C-b Shale Oil Venture, Quarterly Data Releases, Oil Shale Tract C-b, submitted to the Area Oil Shale Supervisor, U.S. Geological Survey, U.S. Department of Interior, 1974 and 1975.

C-b Shale Oil Venture, Environmental Baseline Program, Final Report, Oil Shale Tract C-b, submitted to the Area Oil Shale Supervisor, U.S. Geological Survey, U.S. Department of Interior, 1976.

C-b Shale Oil Venture, Application for a Permit to Inject Water Produced from Oil Shale Tract C-b, submitted to the State of Colorado, February 1979.

Chow, V.T., "On the Determination of Transmissivity and Storage Coefficients from Pumping Test Data," American Geophysical Union Transactions, Vol. 33, pp. 397-404, 1952.

Cooper, H.H., and C.E. Jacob, "A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History," American Geophysical Union Transactions, Vol. 27, pp. 526-534, 1946.

Dansgaard, W., "Stable Isotopes in Precipitation," Tellus, Vol. 16, No. 33, 1964.

Everett, L.G., K.D. Schmidt, R.M. Tinlin, and D.K. Todd, Monitoring Groundwater Quality: Methods and Costs, U.S. Environmental Protection Agency Report 600/4-76-023, May 1976.

Everett, L.G. (editor), Groundwater Quality Monitoring of Western Coal Strip Mining: Identification and Priority Ranking of Potential Pollution Sources, EPA-600/7-79-024, U.S. Environmental Protection Agency, January 1979.

Everett, L.G., Groundwater Monitoring, General Electric Co., Technology Marketing Operation, Schenectady, NY, 1980.

Fox, J.P., R.D. McLaughlin, T.C. Bartke, J.J. Duvall, K.K. Mason, and R.E. Poulson, "Mercury Emissions from a Simulated In Situ Oil Shale Retort," 11th Annual Oil Shale Symposium Proceedings, Golden, Colorado, April 12-14, 1978.

Friedman, I., A.C. Redfield, B. Schoen, and J. Harris, "The Variation of the Deuterium Content of Natural Waters in the Hydrologic Circuit," Reviews of Geophysics, Vol. 2, No. 177, 1964.

Fruchter, J.S., J.C. Laul, M.R. Peterson, P.W. Ryan, and M.E. Turner, "High Precision Trace Element and Organic Constituent Analysis of Oil Shale and Solvent-Refined Coal Materials," ACS New Orleans Meeting, Division of Petroleum Chemistry, Symposium on Analytical Chemistry of Tar Sands and Oil Shale, March 20-25, 1977.

Hamersma, J.W., S.L. Reynolds, and R.F. Maddalone, Level 1 Environmental Assessment, EPA-600/2-76-160a, U.S. Environmental Protection Agency, June 1976.

Hantush, M.S., "Analysis of Data from Pumping Tests in Leaky Aquifers, American Geophysical Union Transactions, Vol. 37, pp. 702-714, 1956.

Hantush, M.S., "Analysis of Data from Pumping Tests in Anisotropic Aquifers," Journal of Geophysical Research, Vol. 71, pp. 421-426, 1966.

Hantush, M.S., and C.E. Jacob, "Non-Steady Radial Flow in an Infinite Leaky Aquifer," American Geophysical Union Transactions, Vol. 36, pp. 95-100, 1955.

Hantush, M.S., and R.G. Thomas, "A Method for Analyzing a Drawdown Test in Anisotropic Aquifers," Water Resources Research, Vol. 2, pp. 281-285, 1966.

Hendricks, D.W., and J.C. Ward, "Environmental Analysis of an Oil-Shale Industry in the Upper Colorado Region," Oil Shale (T.F. Yen and G.V. Chilingarian, editors), 1976.

Hodgson, R.A., Photo Linear Study, MDP Area, Rio Blanco Oil Shale Project, Tract C-a, Gulf R&D Report, March 1979.

Hoering, T.C., and H.E. Moore, "The Isotopic Composition of the Nitrogen in Natural Gases and Associated Crude Oils," Geochemica et Cosmochemica Acta, Vol. 13, No. 225, 1958.

Holt, B.D., A.G. Engelkeneir, and A. Benters, "Variation of Sulfur Isotope Ratios in Samples of Water and Air Near Chicago," *Env. Sci. & Tech.*, Vol. 6, pp. 338-341, 1972.

Horner, D.R., "Pressure Build-up in Wells," *Proceedings, Third World Petroleum Congress*, Vol. 11, p. 503, The Hague, 1951.

Humenick, M.J., L.J. Turk, and M.P. Cochin, "Methodology for Monitoring at Uranium Solution Mines," *Ground Water Journal*, Vol. 18, No. 3, 1980.

Jacob, C.E., "On the Flow of Water in an Elastic Artesian Aquifer," *American Geophysical Union Transactions*, Vol. 72, Part II, pp. 574-586. 1940.

Jensen, M.L., and N. Nakai, "Sources and Isotopic Composition of Atmospheric Sulfur," *Science*, Vol. 134, pp. 2102-2104, 1961.

Johnson Division, UOP Co., *Ground Water and Wells*, Saint Paul, Minnesota, 1966.

Johnson, E.E., *Ground Water and Wells*, Johnson Division, UOP Inc., Saint Paul, Minnesota, 1975.

Kelly, D.P., L.A. Chambers, and P.A. Trudinger, "Cyanolysis and Spectrophotometric Estimation of Trithionate in Mixture with Thiosulfate and Tetrathionate," *Anal. Chem.*, Vol. 41, p. 898, 1969.

Knutson, C.F., *Project Rio Blanco: Evaluation of Possible Radioactivity Transport in Groundwater*, CER Geonuclear Corporation, Las Vegas, Nevada, 1973.

Kruseman, G.P., and N.A. Ridder, *Analysis and Evaluation of Pumping Test Data*, International Institute of Land Reclamation and Improvement, Bulletin II, Wageningen, The Netherlands, 1976.

Leenheer, J.A., and E.W.D. Huffman, Jr., "Classification of Organic Solutes in Water by Using Macroreticular Resins," *Journal Research, U.S. Geological Survey*, Vol. 4, No. 6, p. 737, 1976.

Marsh, J.M., and J.W. Lloyd, "Details of Hydrochemical Variations in Flowing Wells," *Ground Water Journal*, Vol. 18, No. 4, 1980.

Miller, L.M. (editor), *Ground Water*, American Water Well Association, New York, New York, 1973.

Moore, H., "Isotopic Measurement of Atmospheric Nitrogen Compounds," *Tellus*, Vol. 26, No. 167, 1974.

Moore, H., "The Isotopic Composition of Ammonia, Nitrogen Dioxide and Nitrate in the Atmosphere," *Atmos. Environ. II*, No. 1239, 1977.

Neuman, S.P., and P.A. Witherspoon, "Theory of Flow in a Confined Two-aquifer System," *Water Resources Research*, Vol. 5, pp. 803-816, 1969.

Odeh, A.A., and L.G., Jones, "Pressure Drawdown Analysis, Variable Rate Case," Journal of Petroleum Technology, pp. 960-964, August 1965.

Parker, H.W., R.M. Bethea, N. Gunen, M.N. Gazdar, and J.C. Watts, "Interactions Between Ground Water and In Situ Retorted Shale," Proceedings Second Engineering Congress, 1977.

Rio Blanco Oil Shale Company, Quarterly Report, 1974.

Rio Blanco Oil Shale Company, Final Environmental Baseline Report for Tract C-2 and Vicinity, May 1977.

Roboz, J., "Introduction to Mass Spectrometry, Interscience, New York, 1968.

Schmidt, K.D., "Water Quality Variations for Pumping Wells," Ground Water Journal, Vol. 15, No. 2, 1977.

Sievers, R.E., and D. Denny, Investigation of Trace Organic Compounds in Oil Shale Wastes, Progress Report, 1978.

Slawson, G.C. (editor), Groundwater Quality Monitoring of Western Oil Shale Development: Identification and Priority Ranking of Potential Pollution Sources, EPA-600/7-79-023, U.S. Environmental Protection Agency, January 1979.

Slawson, G.C., Jr., Monitoring Groundwater Quality: Monitoring Program Development, GE78TMP-90, General Electric--TEMPO, 1980a.

Slawson, G.C., Jr., Monitoring Groundwater Quality: The Impact of In-Situ Shale Retorting, GE78TMP-103, General Electric--TEMPO, 1980b.

Sokal, R.R., and F.J. Robly, Biometry, W.H. Freeman Co., San Francisco, 1969.

Stuber, H.A., J.A. Leenheer, and D.S. Farrier, Inorganic Sulfur Species in Waste Waters from In Situ Oil Shale Processing, in press.

Summers, W.K., "Factors Affecting the Validity of Chemical Analyses of Natural Water," Ground Water, Vol. 10, No. 1, p. 12-17, 1972.

Summers, W.K., and L.A. Brandvold, "Physical and Chemical Variations in the Discharge of a Flowing Well," Ground Water Journal, Vol. 5, No. 1, 1967.

Theis, C.W., "The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of the Discharge of a Well Using Groundwater Storage," American Geophysical Union Transactions, Vol. 16, pp. 519-524, 1935.

Tiratsou, E.N., Oilfields of the World (2nd Edition), Scientific Press, Ltd., Beaconsfield, England, 1976.

Todd, D.K., R.M. Tinlin, K.D. Schmidt, and L.G. Everett, *Monitoring Groundwater Quality: Monitoring Methodology*, EPA-600/4-76-076, U.S. Environmental Protection Agency, 1976.

U.S. Atomic Energy Commission, *Environmental Statement: Rio Blanco Gas Stimulation Project*, Rio Blanco County, Colorado, April 1972.

U.S. Environmental Protection Agency, *Methods for Chemical Analysis of Water and Wastes*, Report 625/6-74-003, 1974.

U.S. Environmental Protection Agency, *Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities*, Report No. 530/SW-611, prepared for Office of Solid Waste, 1977.

U.S. Environmental Protection Agency, *Methods for Chemical Analysis of Water and Wastes*, Report 600/4-79-020, 1979.

U.S. Geological Survey, "Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases," *Techniques of Water Resources Investigations of the U.S. Geological Survey*, U.S. Government Printing Office, Washington, D.C., 1970.

U.S. Geological Survey, *Inflatable Straddle Packers and Associated Equipment for Hydraulic Fracturing and Hydrologic Testing*, Water Resources Investigations 78-55, PB 288-403, 1978.

Wada, E., T. Kadonga, and S. Matsuo, "^{15}N Abundance in Nitrogen of Naturally Occurring Substances and Global Assessment of Denitrification from Isotopic Viewpoint," *Geochemical Journal*, Vol. 9, No. 139, 1975.

Walton, W.C., *Selected Analytical Methods for Well and Aquifer Evaluation*, Illinois State Water Survey Bulletin No. 49, 1962.

Weeks, J.B., G.H. Leavesley, F.A. Welder, and G.J. Saulnier, Jr., *Simulated Effects of Oil Shale Development on the Hydrology of Piceance Basin, Colorado*, U.S. Geological Survey Professional Paper 908, 1974.

Welch, P.S., "Limnological Methods." (Cited in Everett 1976).

Welder, F.A., and G.J. Saulnier, Jr., *Geohydraulic Data from Twenty-four Test Holes Drilled in the Piceance Basin, Rio Blanco County, Colorado, 1976-76*, U.S. Geological Survey Open File Report 78-734, 1978.

Wood, W., "Guidelines for Collection and Field Analysis of Ground-Water Samples for Selected Unstable Constituents," *Techniques of Water-Resource Investigations*, Book 1, Chapter D2, U.S. Geological Survey 1976.

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